

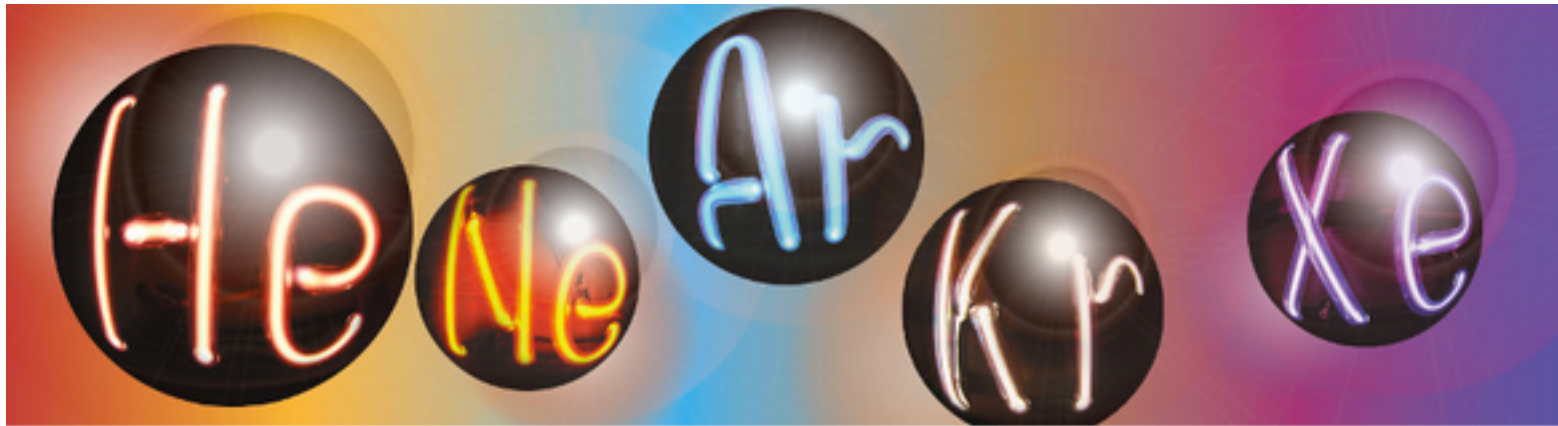
Superfluid Helium for Low-Mass Dark Matter Detection

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(with much content from Scott Hertel, UCB -> UMass)



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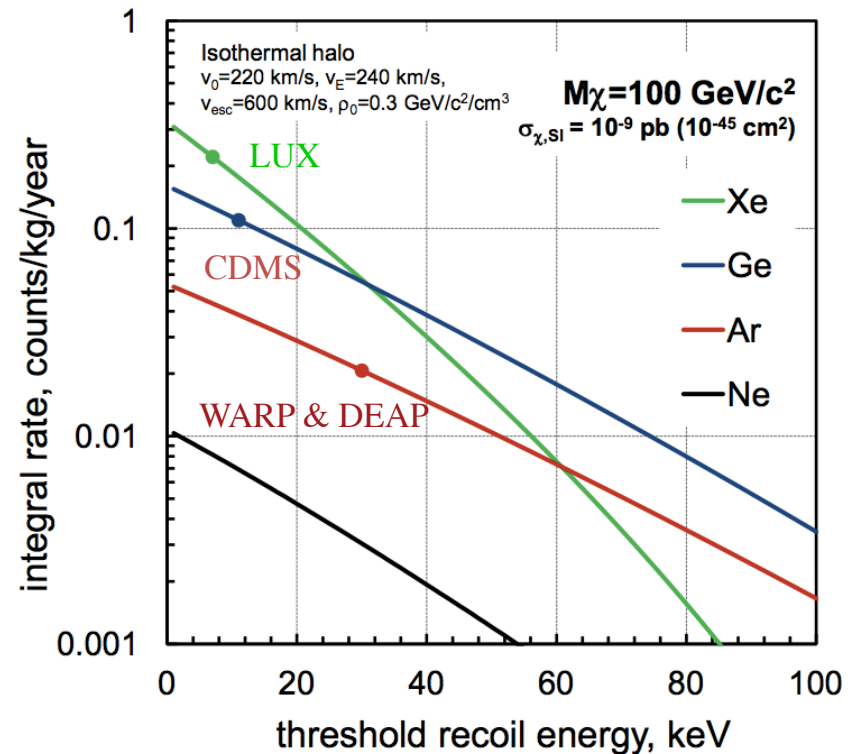
Weakly Interacting Massive Particle (WIMP) Direct Detection

Look for anomalous nuclear recoils in a low-background detector.

$R = N \rho \langle \sigma v \rangle$. From $\langle v \rangle = 220$ km/s, get order of 10 keV deposited.

Requirements:

- Low radioactivity
- Deep underground laboratory
- Low energy threshold
- Gamma ray rejection
- Scalability



Experimental Background Reduction

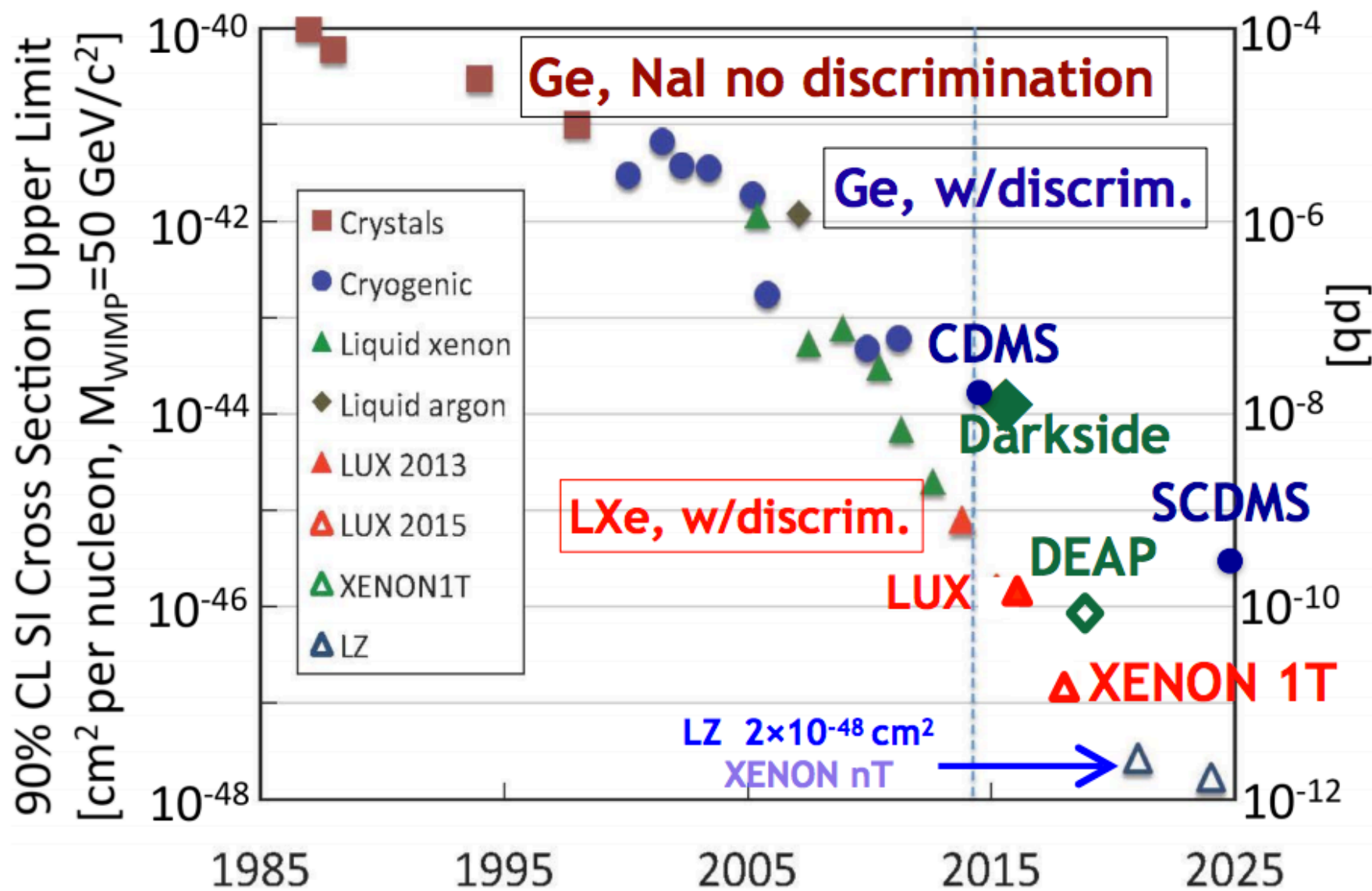
- Neutrons: Can be remediated through shielding, careful choice and screening of detector materials, cutting multiple scatter events, and by fiducializing detector volume, if it is self-shielding, and by simulating all of the neutron sources you've determined.
- Alpha particles: Radon events near detector walls can be removed from data by good fiducialization. However (alpha,n) events remain problematic (above) even for scintillators, even if alphas themselves bright
 - As with neutrons above, material screening and simulations help a great deal here
- Gammas and electrons: Reduce using component screening, shielding. It can help enormously if your detector is insensitive to electron recoils, or can discriminate between electron and nuclear recoils well (between 1 part in 10^3 - 10^{11} level discrimination/acceptance possible with current detectors)
 - High energy gamma rays -> multiple-scattering; self-shielding -> fiducialization.
- Muons: Can go deep underground to help shield. Can also tag them with muon veto (Cerenkov-capable water tank, plastic scintillator panels, etc.)
- Detector-originated backgrounds: Electrons emitted from grids and photoionized impurities, photodetector dark counts, leakage currents, vibrations. These detector effects typically limit low-energy thresholds, and are specific to particular detector. Detector-originated backgrounds can be substantially reduced by having 2 or more signal channels.
- Neutrinos: Can't be shielded. But electron recoils removed through discrimination.
- Can also exploit the expected daily variation in dark matter track direction, or seasonal variation in dark matter signal rate. These can be thought of as lock-in amplifiers for dark matter signal, giving another handle on background reduction.

Experimental Background Reduction

When designing an experiment, background considerations are typically more important than signal considerations, in the sense that backgrounds vary over more orders of magnitude.

Typical high-quality shielding allows radioactive background rate ~ 1 event/keV/kg/day.

We are approaching signal rates some 5-7 orders of magnitude smaller than this, requiring some set of background rejection capabilities to be incorporated into the experimental design.



The Noble Liquid Revolution

Noble liquids are relatively inexpensive, easy to obtain, and dense.

Easily purified

- low reactivity
- impurities freeze out
- low surface binding
- purification easiest for lighter noble liquids

Ionization electrons may be drifted through the heavier noble liquids

Very high scintillation yields

- noble liquids do not absorb their own scintillation
- 30,000 to 40,000 photons/MeV
- modest quenching factors for nuclear recoils

Easy construction of large, homogeneous detectors

Liquified Noble Gases: Basic Properties

Dense and homogeneous

Do not attach electrons, heavier noble gases give high electron mobility

Easy to purify (especially lighter noble gases)

Inert, not flammable, very good dielectrics

Bright scintillators

| | Liquid density (g/cc) | Boiling point at 1 bar (K) | Electron mobility (cm ² /Vs) | Scintillation wavelength (nm) | Scintillation yield (photons/MeV) | Long-lived radioactive isotopes | Triplet molecule lifetime (μs) |
|-----|-----------------------|----------------------------|---|-------------------------------|-----------------------------------|------------------------------------|--------------------------------|
| LHe | 0.145 | 4.2 | low | 80 | 19,000 | none | 13,000,000 |
| LNe | 1.2 | 27.1 | low | 78 | 30,000 | none | 15 |
| LAr | 1.4 | 87.3 | 400 | 125 | 40,000 | ³⁹ Ar, ⁴² Ar | 1.6 |
| LKr | 2.4 | 120 | 1200 | 150 | 25,000 | ⁸¹ Kr, ⁸⁵ Kr | 0.09 |
| LXe | 3.0 | 165 | 2200 | 175 | 42,000 | ¹³⁶ Xe | 0.03 |

Radiative decay of the metastable $\text{He}_2(a^3\Sigma_u^+)$ molecule in liquid helium

D. N. McKinsey, C. R. Brome, J. S. Butterworth, S. N. Dzhosyuk, P. R. Huffman, C. E. H. Mattoni, and J. M. Doyle
Department of Physics, Harvard University, Cambridge, Massachusetts 02138

R. Golub and K. Habicht
Hahn-Meitner Institut, Berlin-Wannsee, Germany
 (Received 27 July 1998)

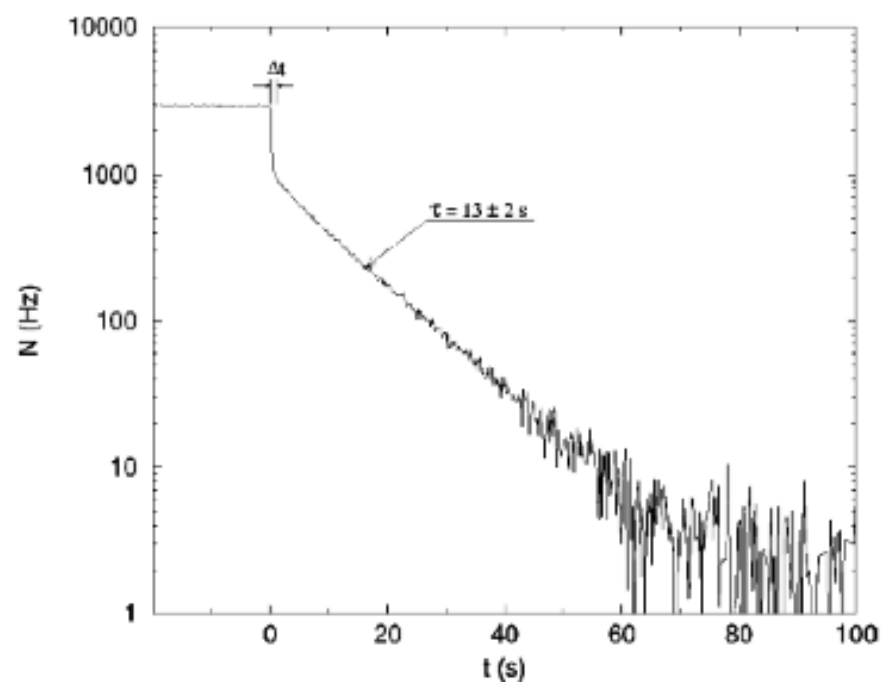
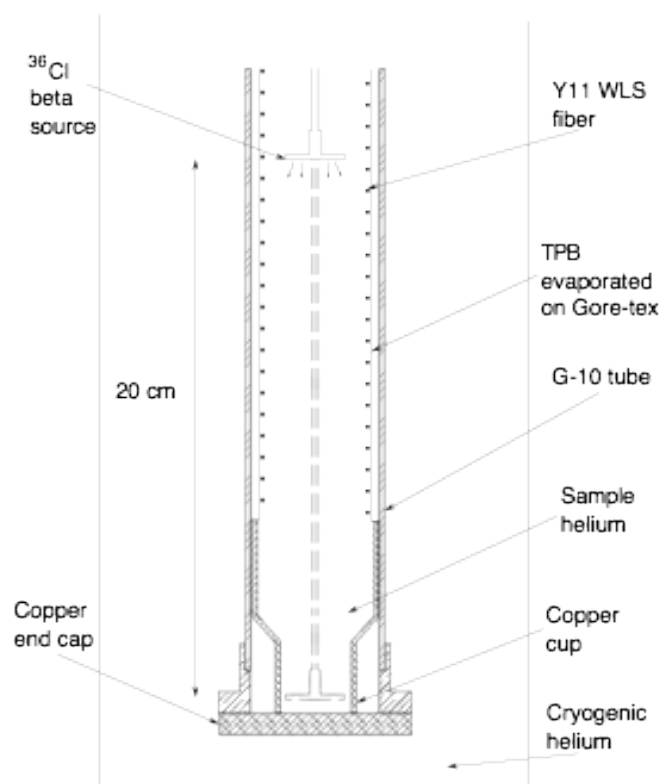
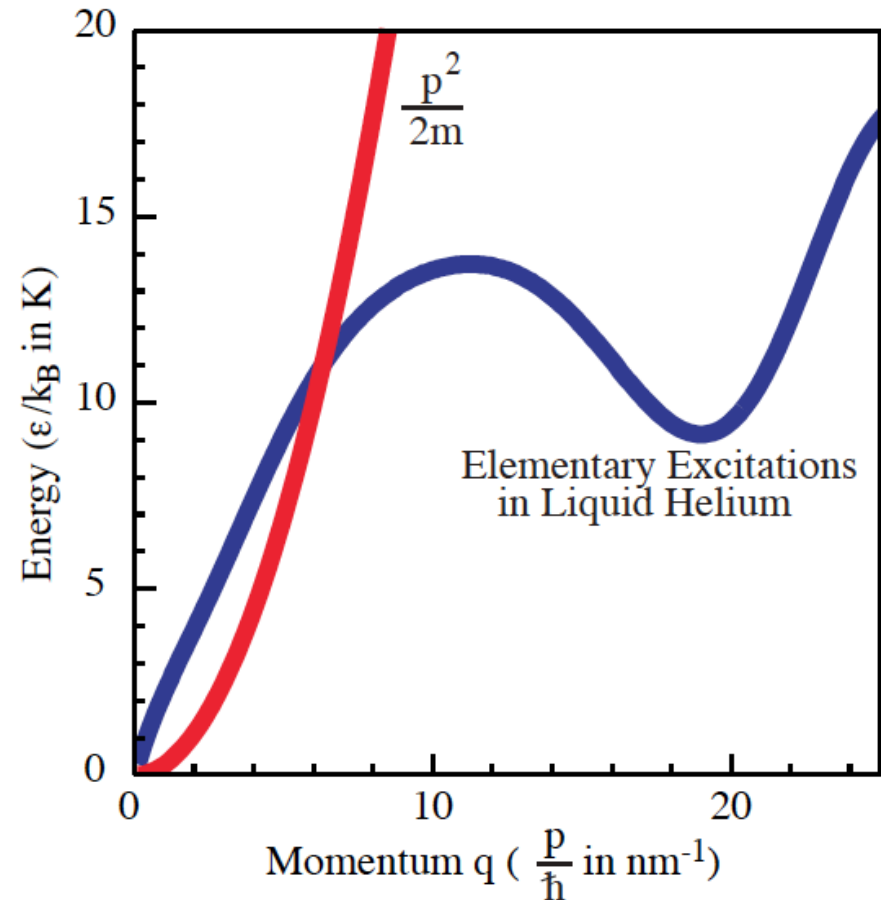


FIG. 2. Count rate N of detected $\text{He}_2(a^3\Sigma_u^+)$ decays versus time. A ^{36}Cl β source is placed in the center of the detection region and then removed in a time $\Delta t < 1$ s. This measurement was performed at a temperature of 1.8 K and resulted in a measured decay rate τ of 13 ± 2 s.

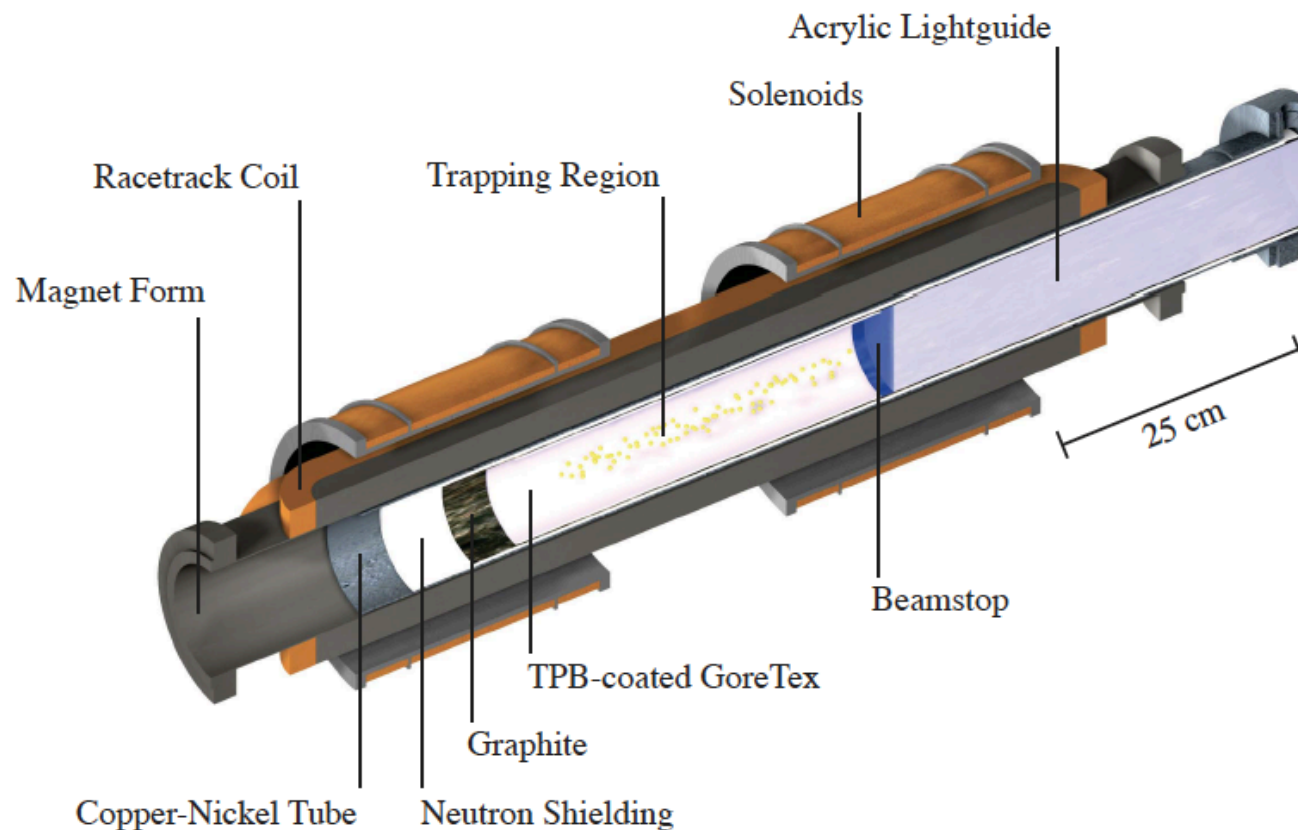
Superfluid helium-4 as a detector material

- Used to produce, store, and detect ultracold neutrons.
 - Production based on “superthermal effect”: direct production of phonons by cold neutrons, allowing the neutrons to scatter to 100 neV-scale energies and be captured by magnetic fields or material bottles.
 - Can store the neutrons within the superfluid helium; neutrons cannot absorb on He-4.
 - Detection based on scintillation light.



Superfluid helium-4 as a detector material

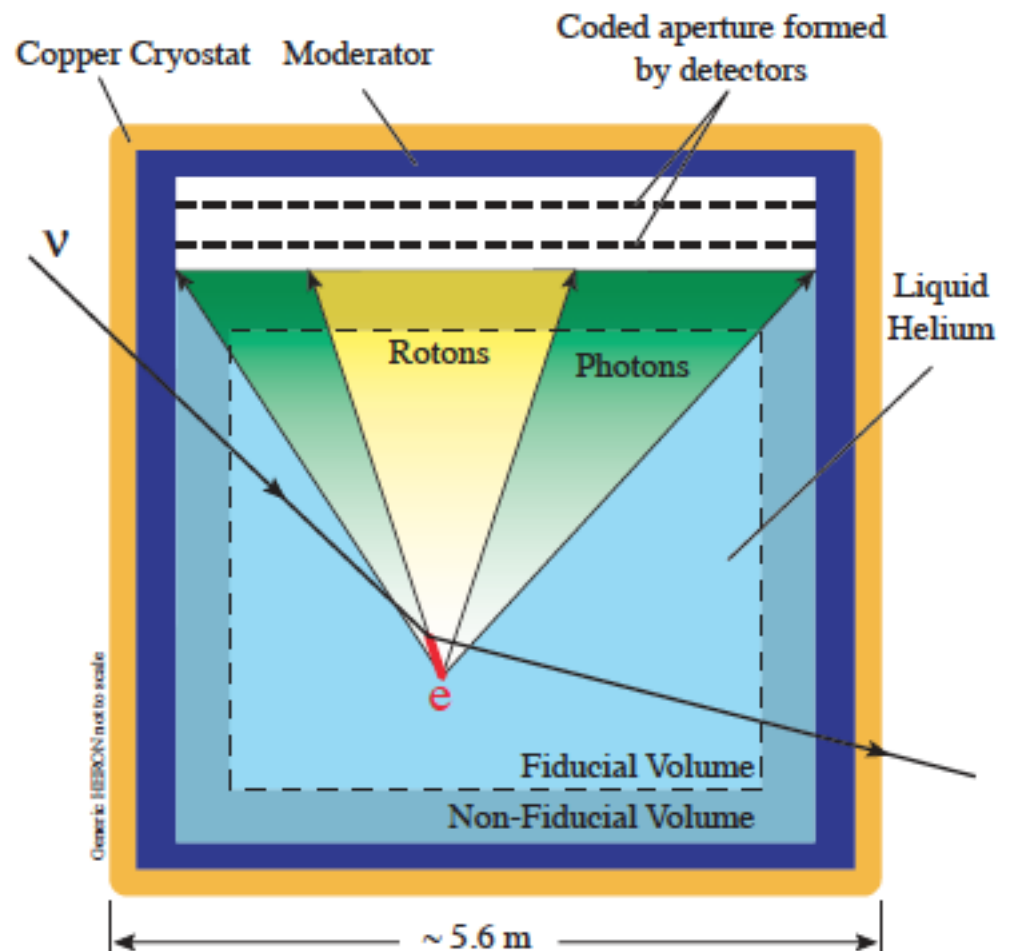
- Search for the neutron electric dipole moment: R. Golub and S.K. Lamoreaux, Phys. Rep. **237**, 1-62 (1994).
Measurement of neutron lifetime: P.R. Huffman et al, Nature **403**, 62-64 (2000).



Superfluid helium-4 as a detector material

Proposed for **measurement of pp solar neutrino flux** using roton detection (HERON): R.E. Lanou, H.J. Maris, and G.M. Seidel, Phys. Rev. Lett. **58**, 2498 (1987).

Two signal channels, heat and light. Both measured with a bolometer array.



Why Superfluid Helium for Low-mass Dark Matter Detection?

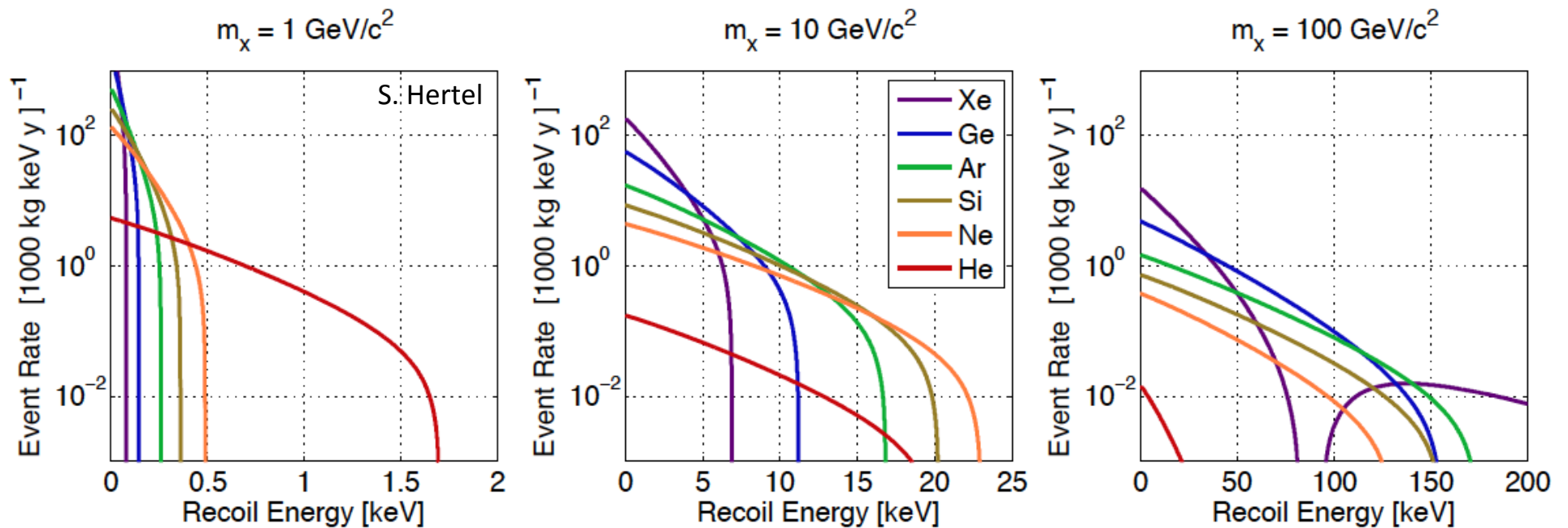
- Kinematic matching with light dark matter candidates.
 - Pull the energy depositions up in energy, to above threshold.
 - Gain access to more of the WIMP velocity distribution, for a given energy threshold.
 - New: access to extremely low mass dark matter through multi-excitation production, back-to-back jets (K. Schutz and K. Zurek, Phys. Rev. Lett. 117, 121302 (2016) and S. Knapen, T. Lin, and K. Zurek, arXiv:1611.06228).
- Superfluid helium offers multiple signals to choose from, and to separate dark matter signal from backgrounds (both electron recoils and detector backgrounds).
 - Prompt light
 - Delayed triplet excimers
 - Charge
 - Heat (roton and photon quasiparticles)

Why Superfluid Helium?

- Liquid down to 0 K, allowing 10-100 mK-scale TES readout.
 - Take advantage of the great advances in TES technology
 - Take advantage of possible $\sim 100\%$ detection efficiency for photons, triplet excimers
 - Take advantage of the extremely low vapor pressure of superfluid helium at low temperatures, enabling quantum evaporation-based heat signal amplification.
- Helium is expected to have robust electronic excitation production efficiency, with a forgiving Lindhard factor, so nuclear recoil scintillation signals should be relatively large.
- Negligible target cost
- Low nuclear mass and charge \rightarrow low backgrounds from neutrino-nucleus scattering and gamma-nucleus scattering.
- Low vibration sensitivity: As a superfluid, small velocities don't generate excitations.
- Large ionization gap \rightarrow less signal quanta per keV than in super-, semiconductors. But no electron recoil background below 14 eV.
- Impurities easily removed from helium using cold traps and getters, and will literally fall out of the superfluid.

Helium-4 Nuclei: A Natural Match for Light Dark Matter Detection

Lose overall recoil rate as A^2 , but gain rate above some energy threshold

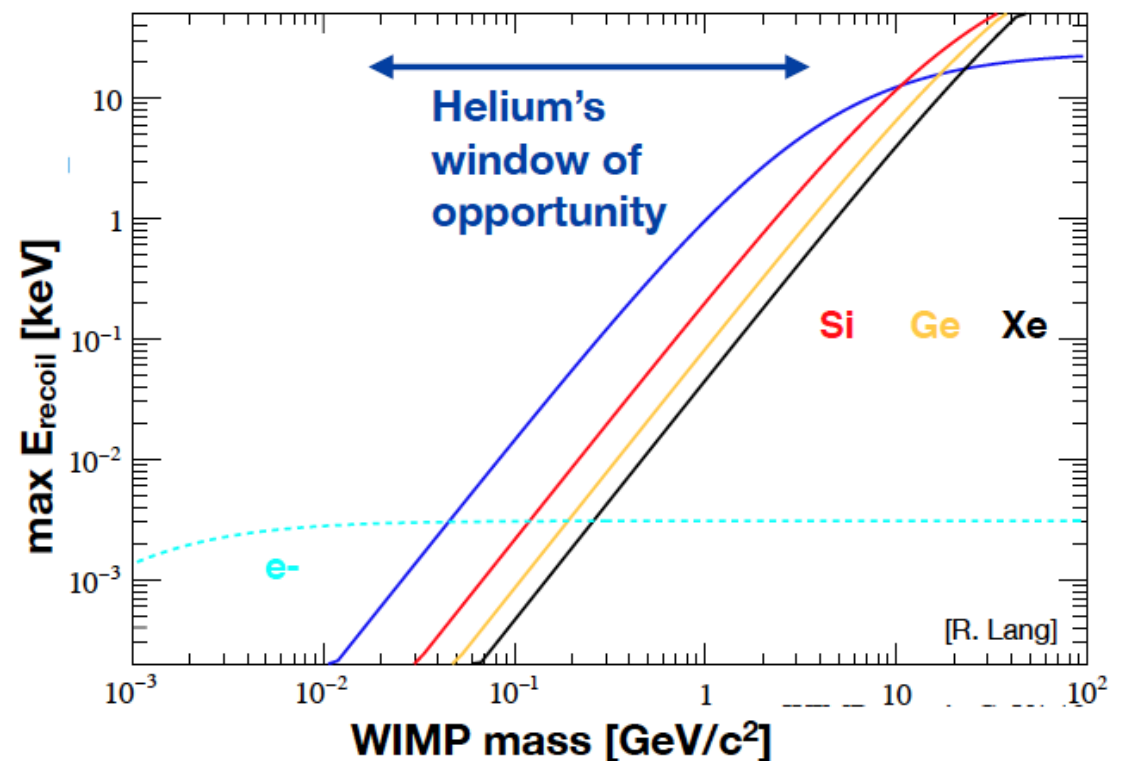


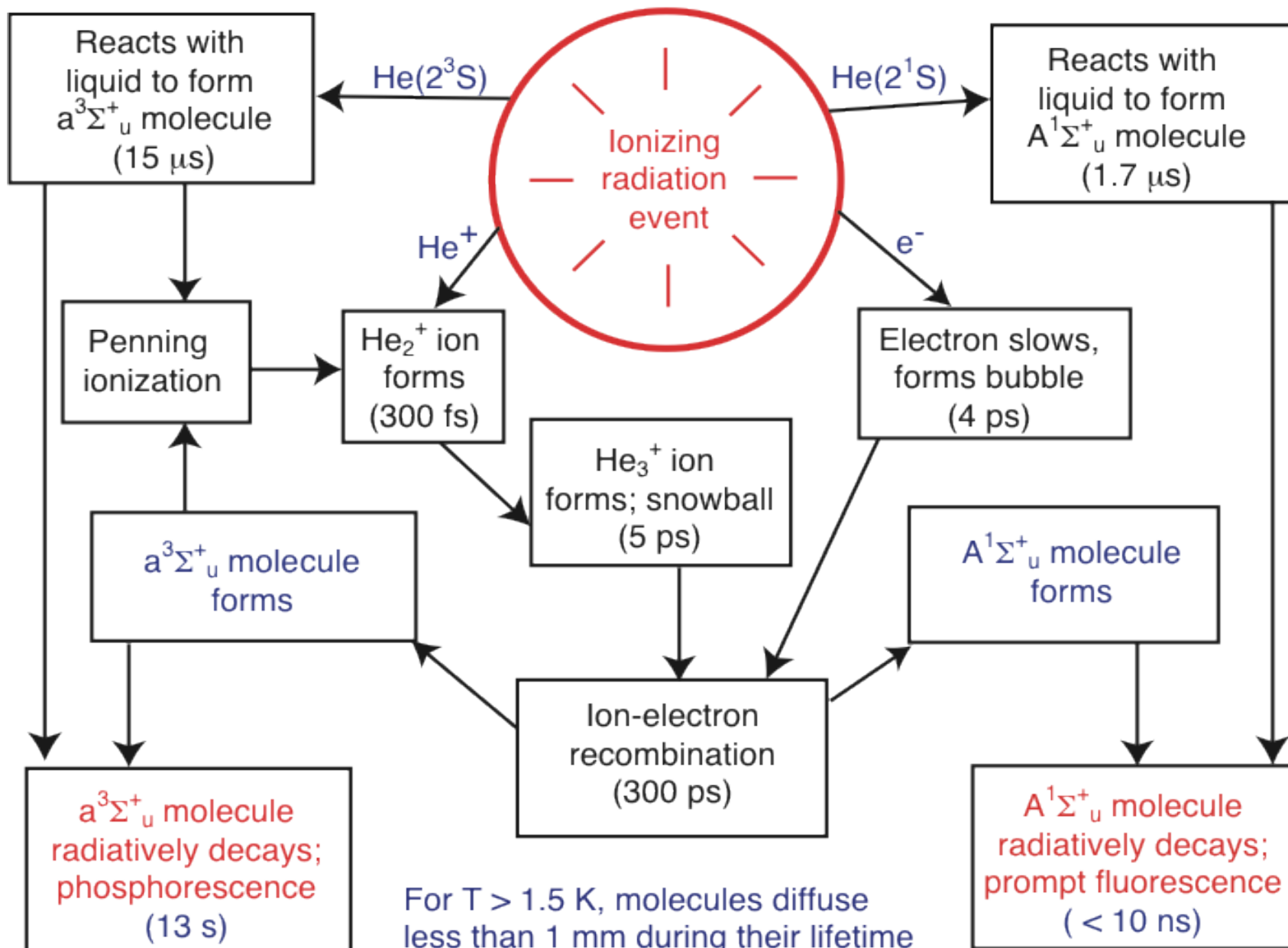
Helium-4 Nuclei: A Natural Match for Light Dark Matter Detection

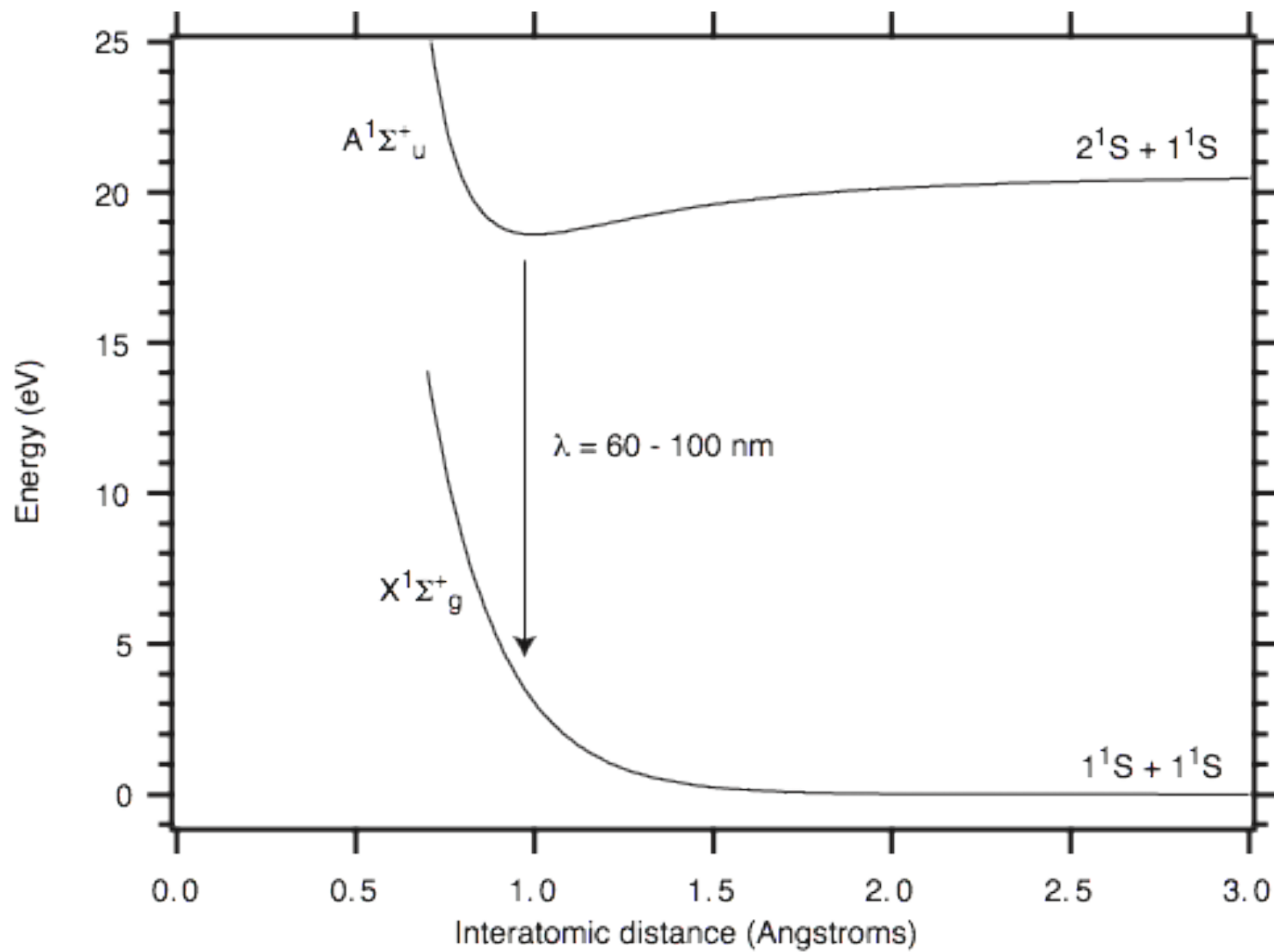
Another view: maximum recoil energy for various targets, as a function of WIMP mass.

$$\max E_{\text{recoil}} = KE_x \left(\frac{4 m_t m_x}{(m_t + m_x)^2} \right)$$

here,
 v_x = galactic escape velocity, 540 km/s
nuclear form factors completely ignored
electron's atomic state similarly ignored

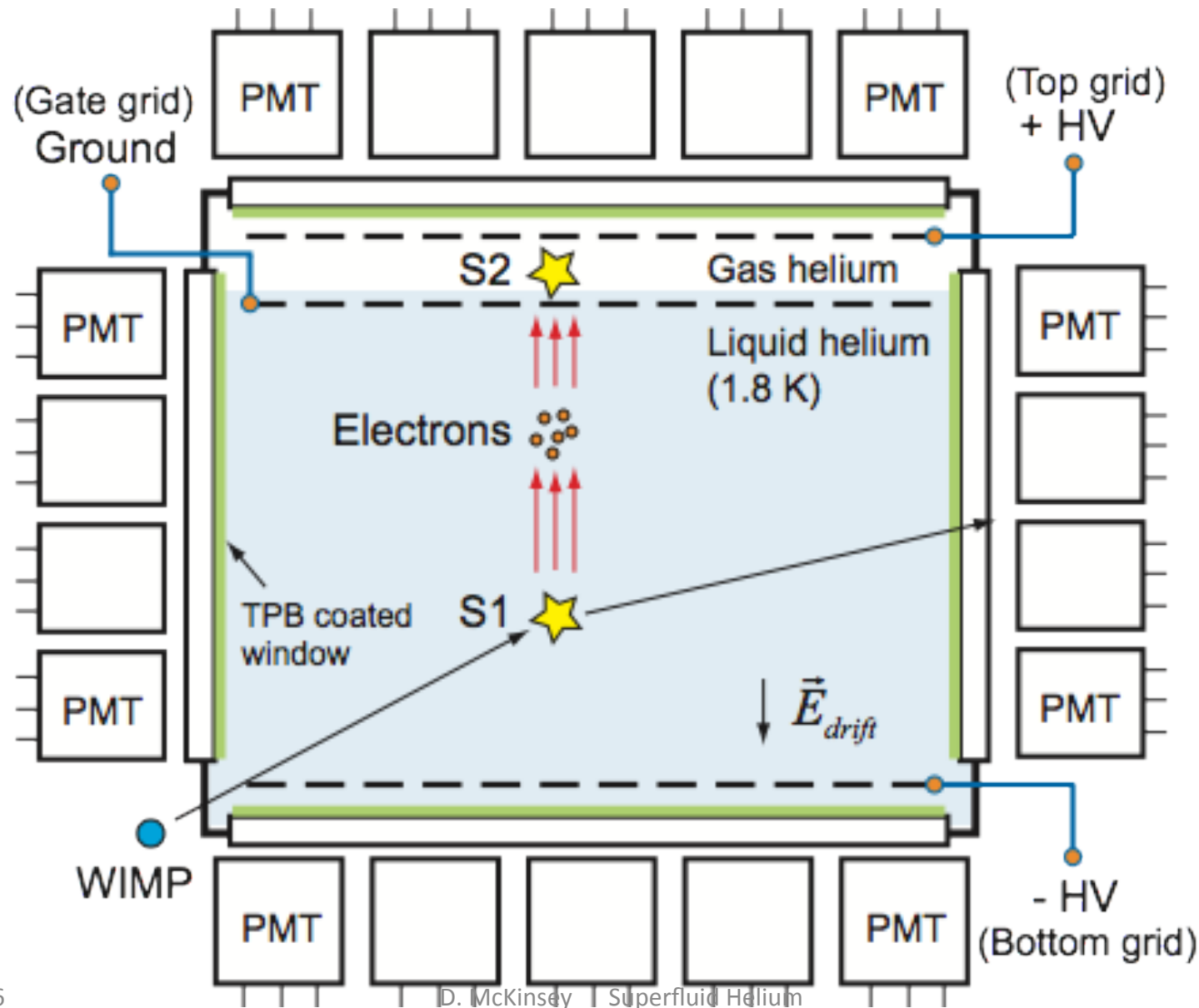




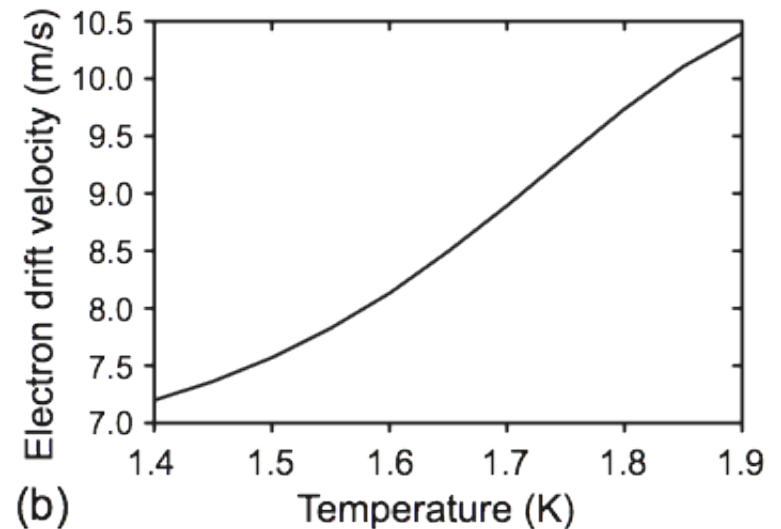
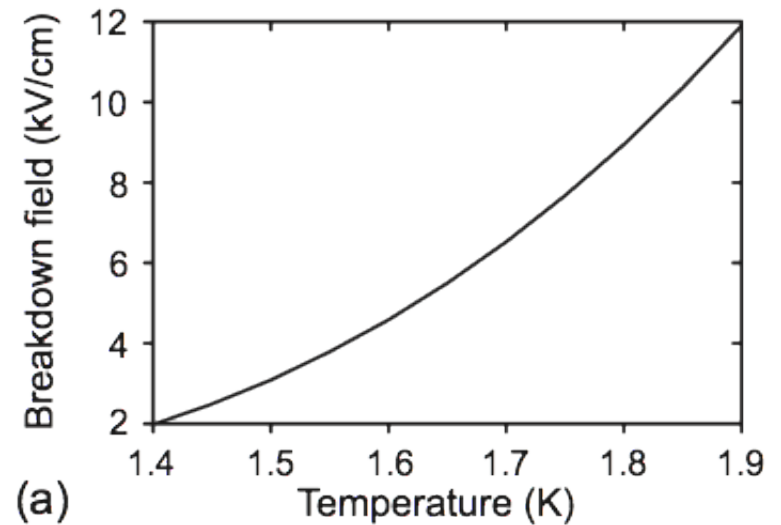
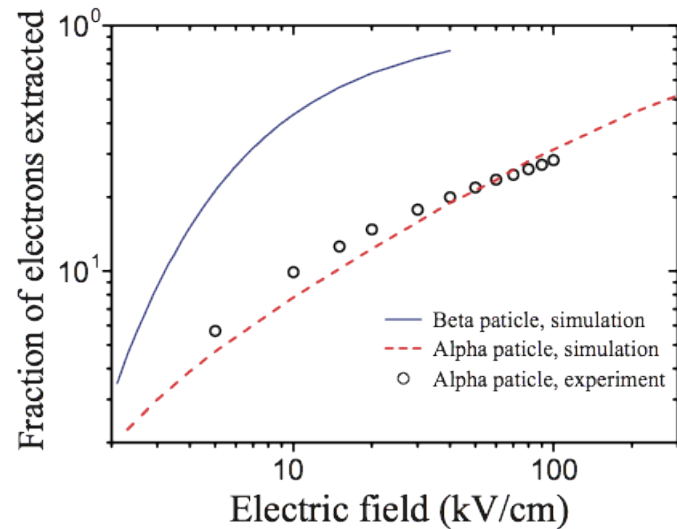
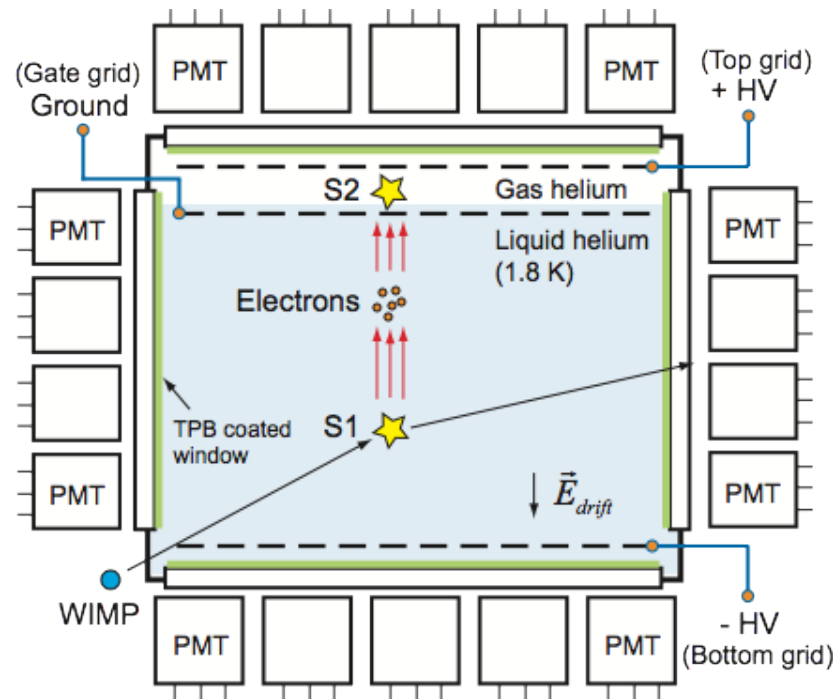


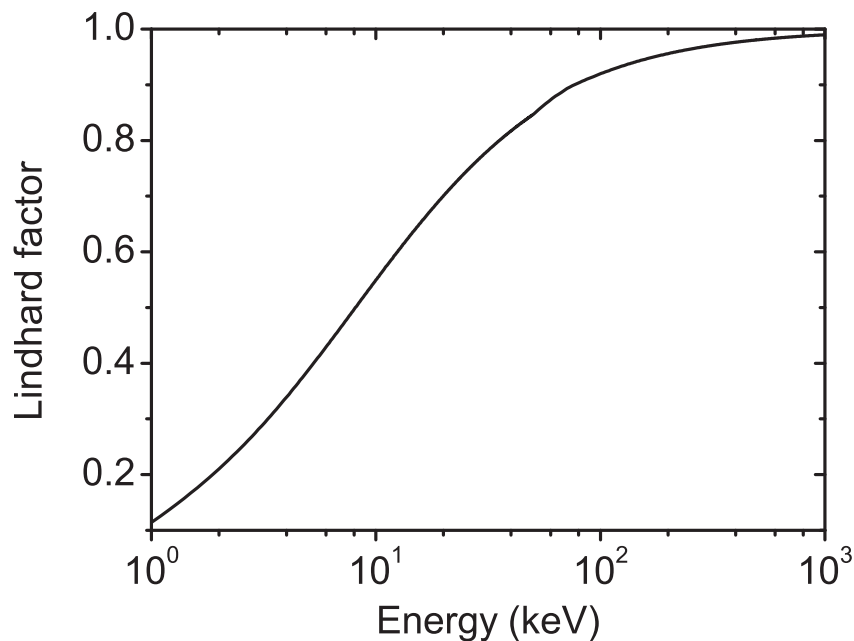
Light WIMP Detector Concept #1: Two-Phase Helium

Energies down to ~ 1 keV. Best for searches > 2 GeV.



A two-phase helium detector; salient properties

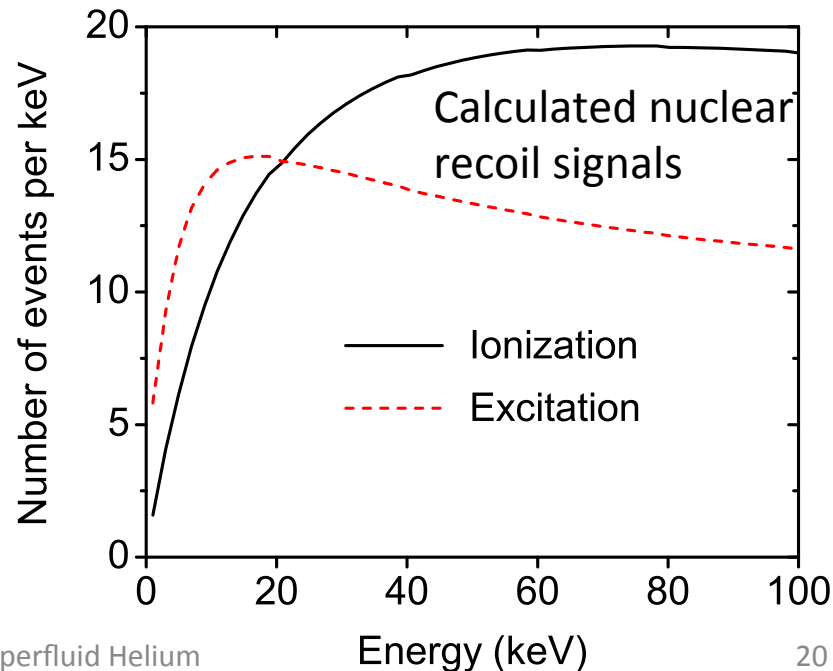
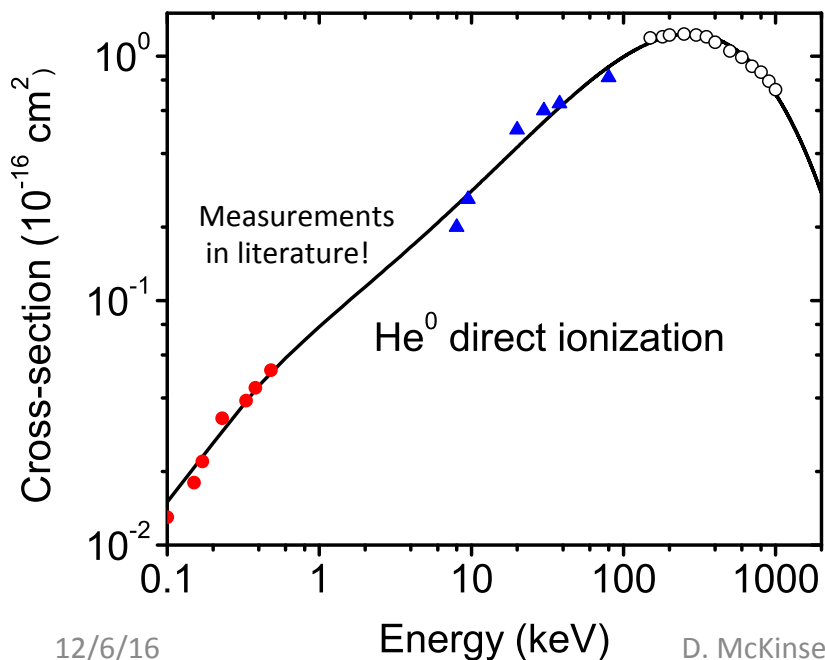




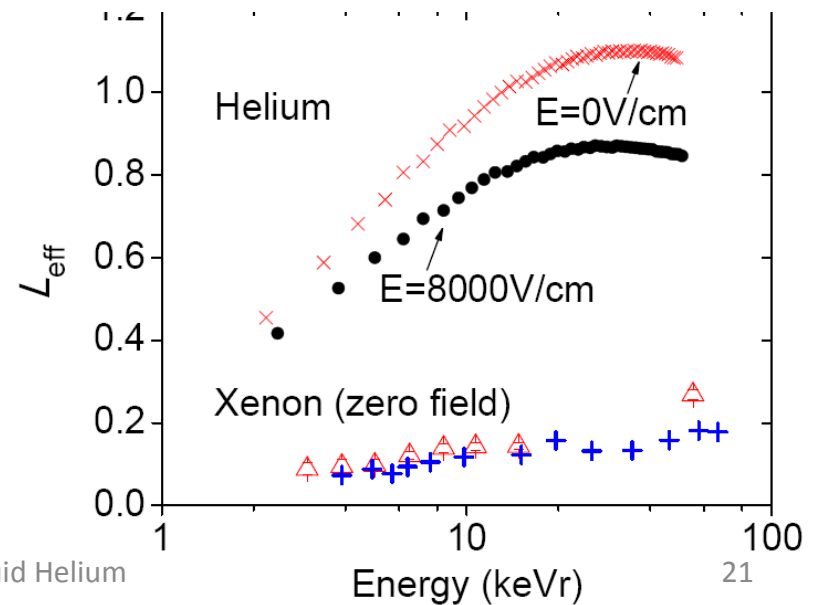
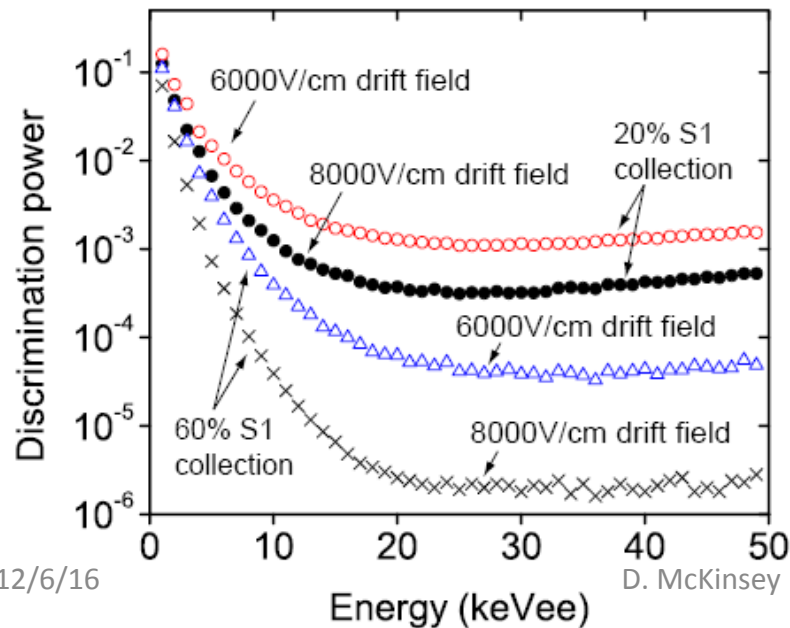
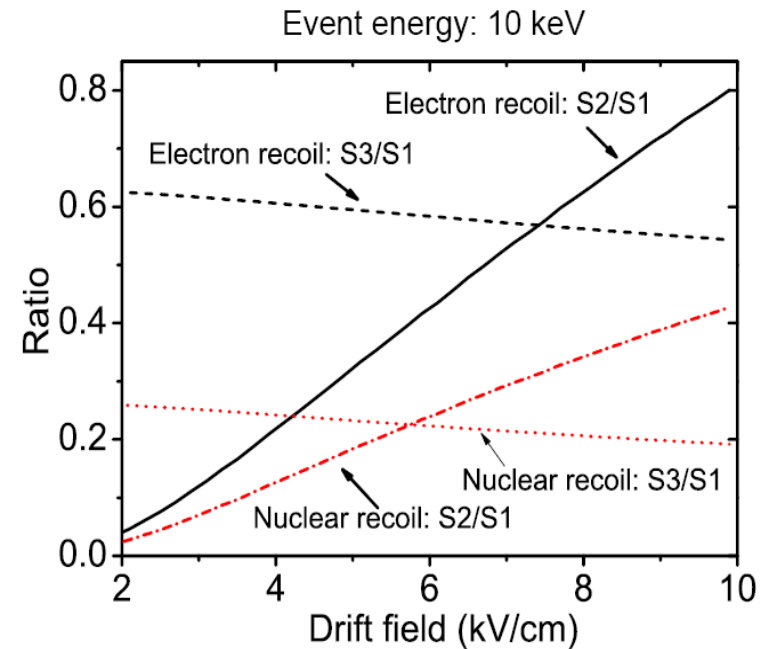
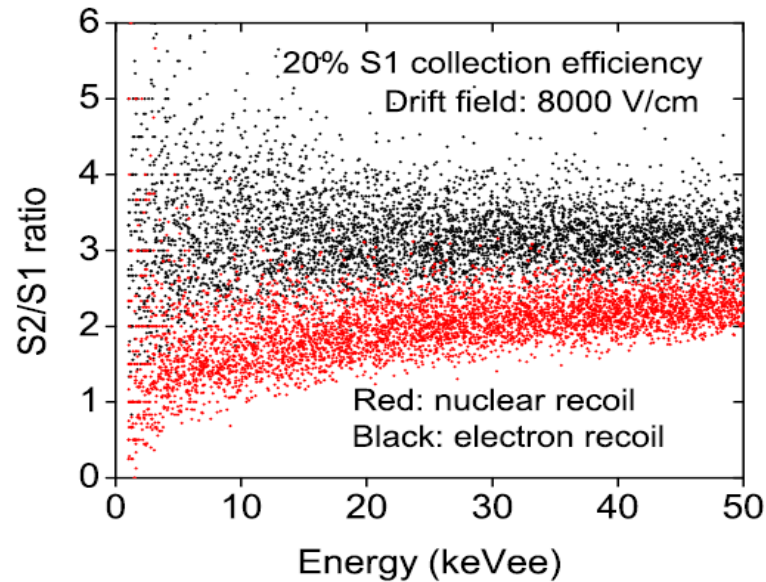
Liquid helium-4 predicted response
(Guo and McKinsey, arXiv:1302.0534,
Phys. Rev. D 87, 115001 (2013).)

Liquid helium has lower electron scintillation
yield for electron recoils (19 photons/keVee)

But, extremely high L_{eff} , good charge/light
discrimination and low nuclear mass for
excellent predicted light WIMP sensitivity



Predicted nuclear recoil discrimination and signal strengths in liquid helium



How to detect triplet helium molecules?

Detect with TES array immersed in superfluid, and let the molecules travel ballistically to be detected ($v \sim 1\text{-}10\text{ m/s}$)

- $< 1\text{ eV}$ resolution quite possible
- Each molecule has $\sim 18\text{ eV}$ of internal energy, which will mostly be released as heat, electronic excitation in TES.
- Note that the same bolometer array could detect both light and triplet excimers!
- Now has been demonstrated experimentally.

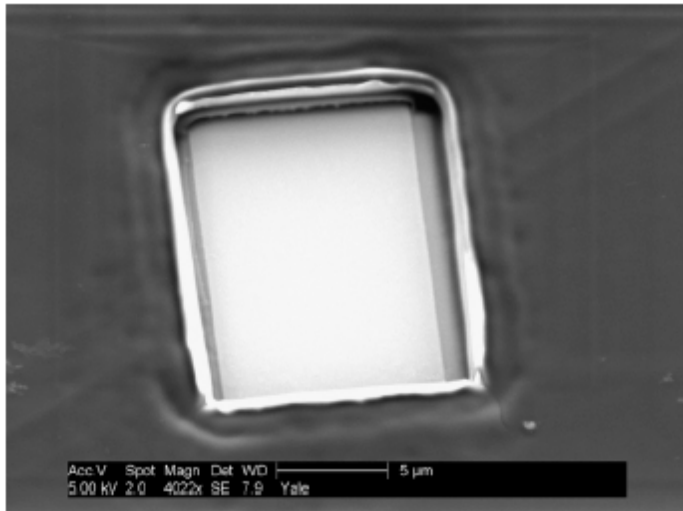
How to detect triplet helium molecules?

New demonstration: Transition Edge Sensor operated immersed in superfluid helium
See F. Carter et al, arXiv:1605.00694

Calorimetric observation of single He_2^* excimers in a 100 mK He bath

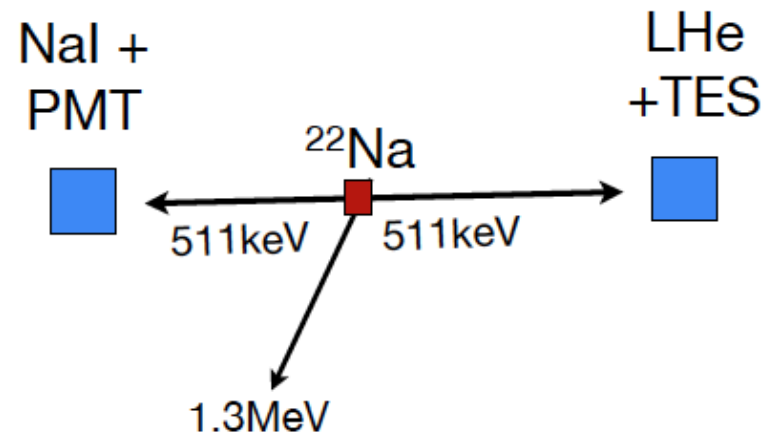
F.W. Carter,^{1,2,a} S.A. Hertel,^{3,4,2} M.J. Rooks,⁵ P.V.E. McClintock,⁶ D.N. McKinsey,^{3,4,2} and D.E. Prober⁷

The collection area here is just the transition edge sensor itself
Microscopic. One (max) excitation per recoil.



Coincidence: prompt singlet photon

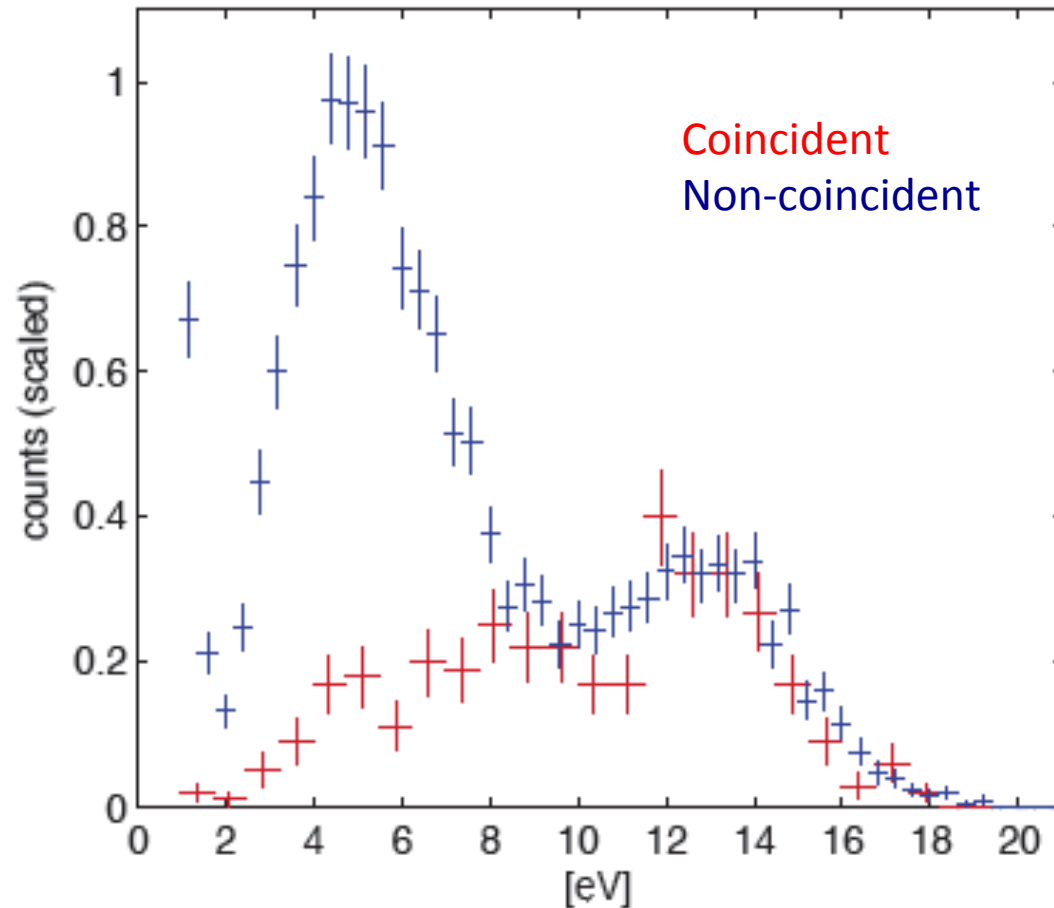
Non-coincidence: delayed triplet molecule
(+untagged photons)



How to detect triplet helium molecules?

Use the same array of TES sensors!

See F. Carter et al, J Low Temp Phys (2016),
doi:10.1007/s10909-016-1666-x, arXiv:1605.00694



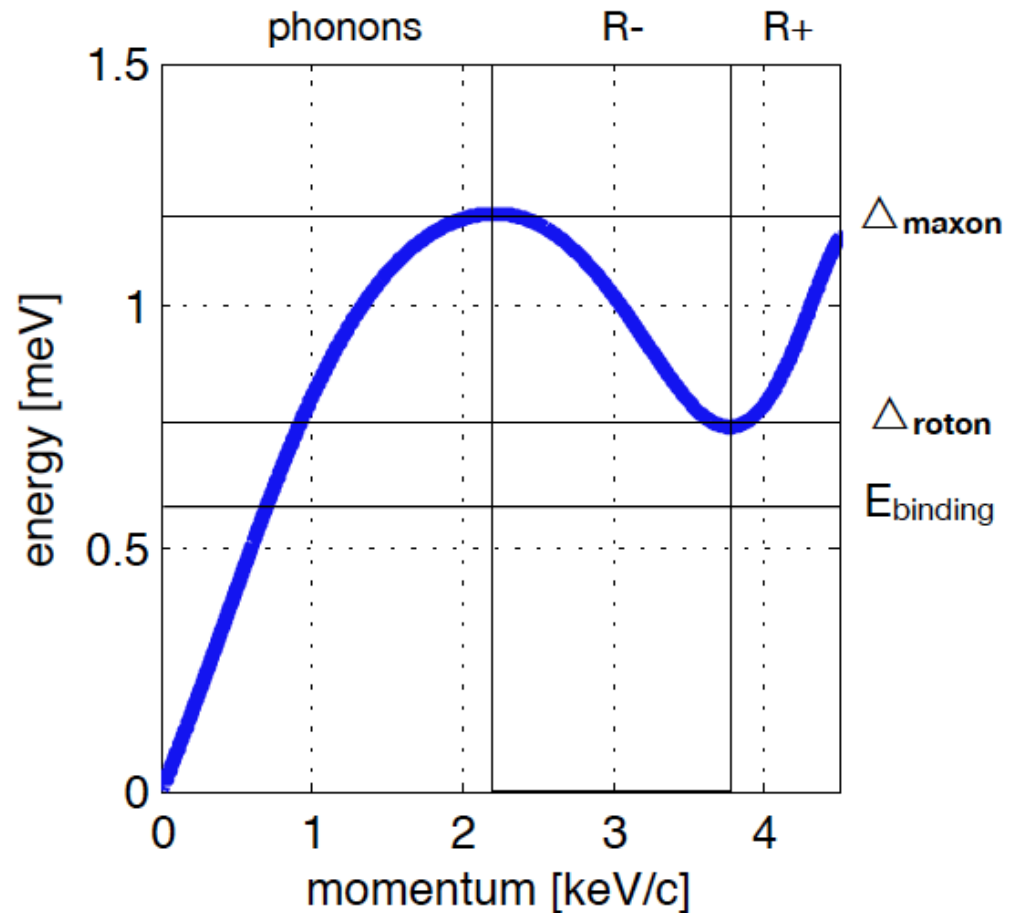
Phonons and Rotons

Superfluid supports vibrational modes
(some non-intuitive)

Ballistic, ~ 150 m/s

Enormous Kapitza resistance,
i.e. *tiny* probability of crossing into solid

Few downconversion pathways



Athermal Evaporation – Demonstrated by HERON R&D

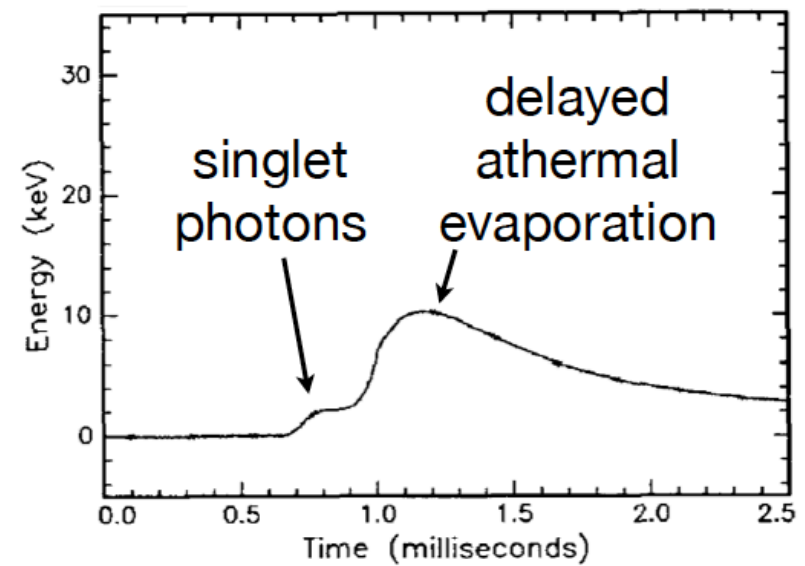
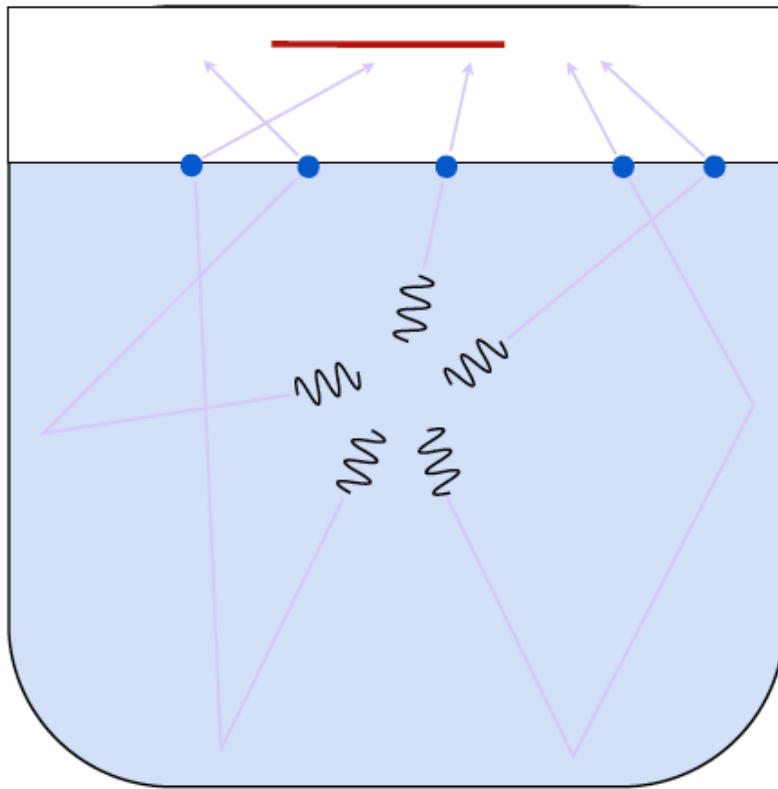
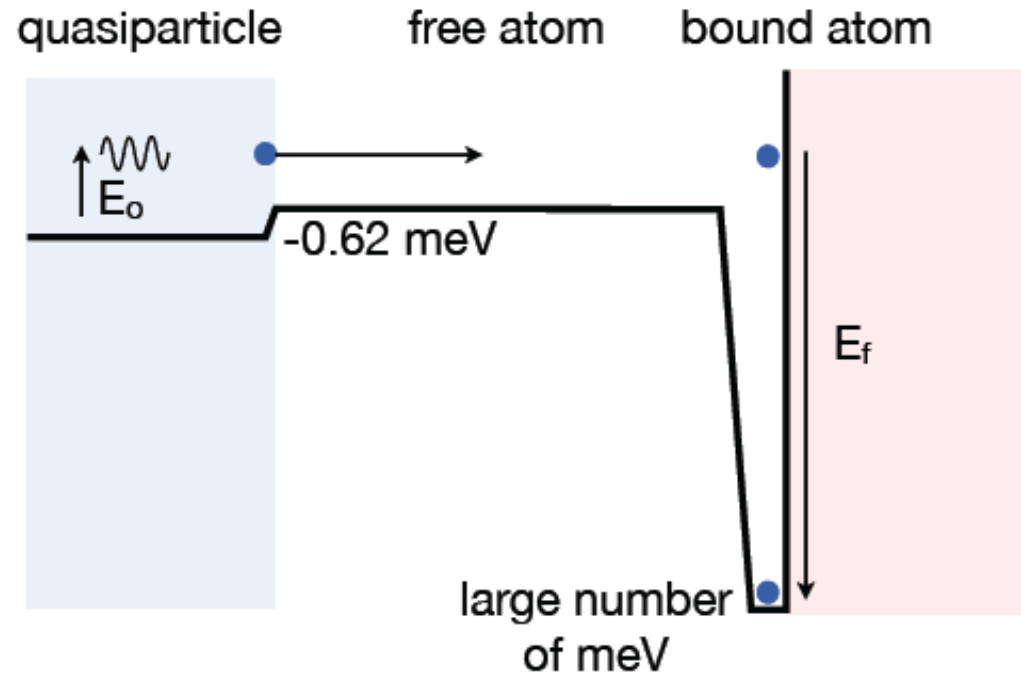


Fig. 2. (a) The calorimeter response (average of about 100 events) when an α particle is stopped in liquid helium. The collimated α tracks are (a) parallel and (b) perpendicular to the liquid surface.

Quantum evaporation from superfluid helium – vacuum interface

Heat amplification from desorption – adsorption process
Adsorption gives 10-40 meV depending on surface

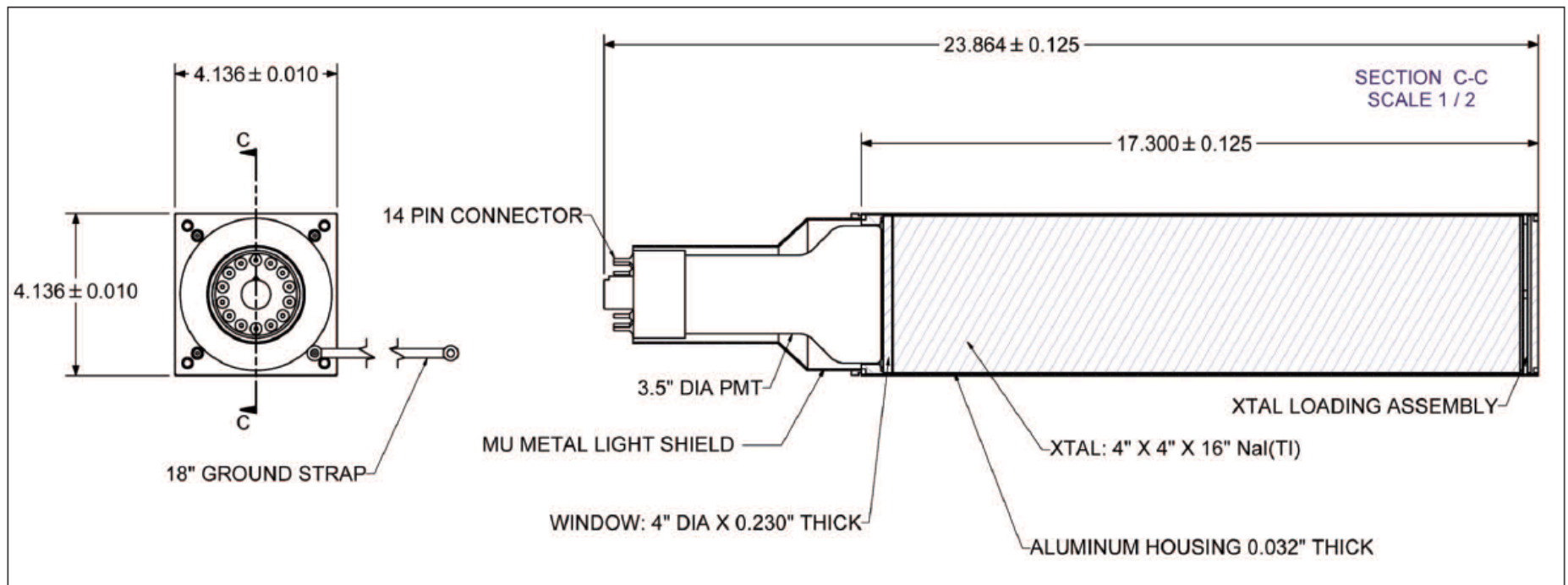


A mirrored box for heat collection

Analogy with light detectors, which collect scintillation light from a crystal or scintillating liquid, using a reflector around the scintillator to efficiently steer the light into a photomultiplier.

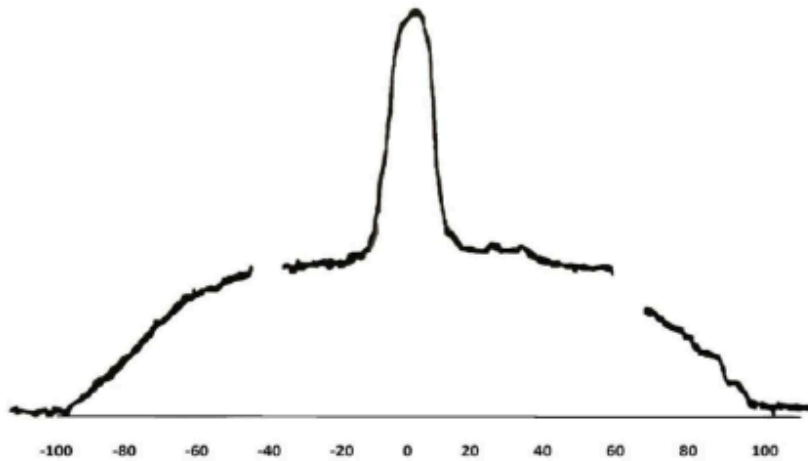
Here is a standard NaI detector, this one from Ortec:

905-16 NaI Scintillation Detector, 4- x 4-in. crystal, 3-in. tube

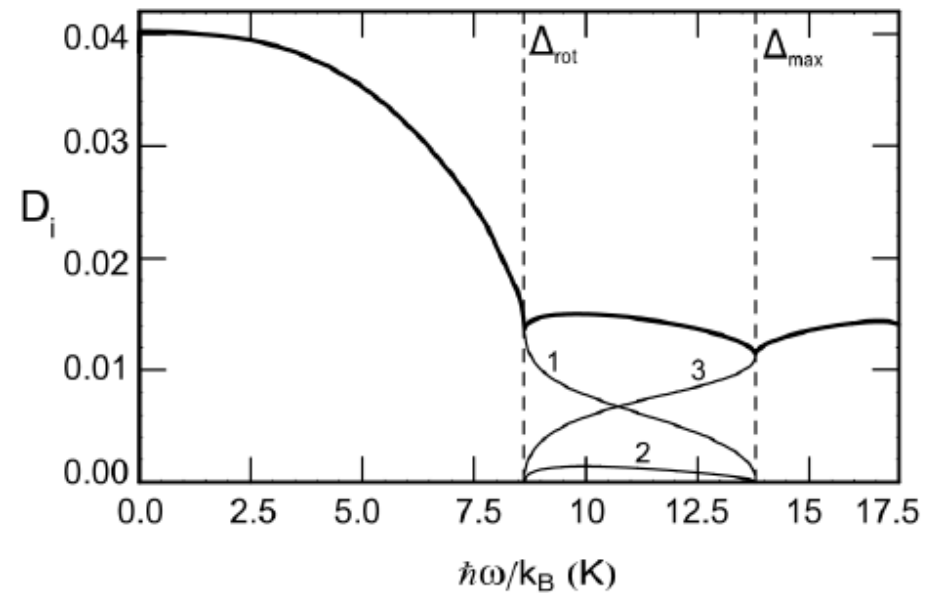


Phonon/roton conversion into solid surfaces is rare

Only at normal incidence



... and then with only ~1.5% probability



arXiv:1004.3497v1

Concept #2

Signal channels:

- 1) Scintillation
- 2) Ballistic Triplet Excimers
- 3) Phonons/Rotons

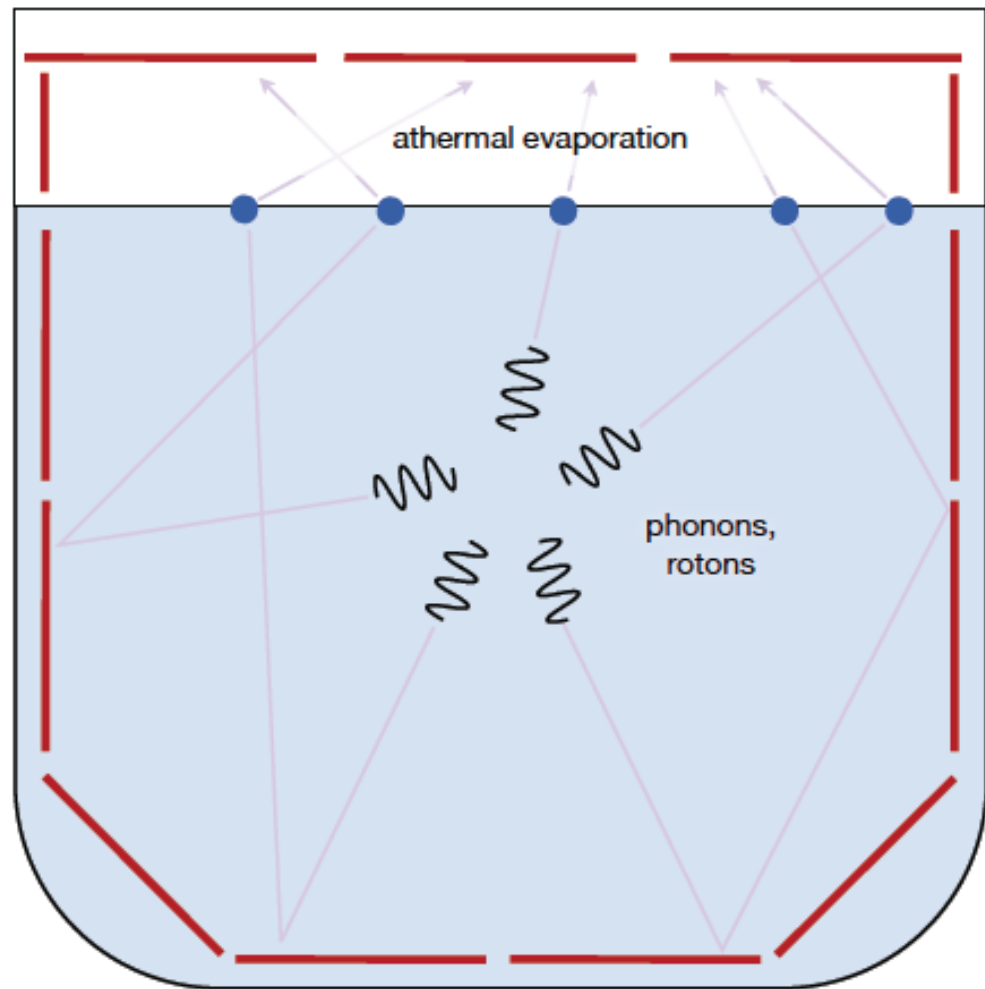
No drift field, and no S2 signal

- no worry of few-electron background
- Position reconstruction via signal hit patterns
- (Though could apply drift field to detect single electrons via roton/phonon production.)

Best for energies down to 300 eV.

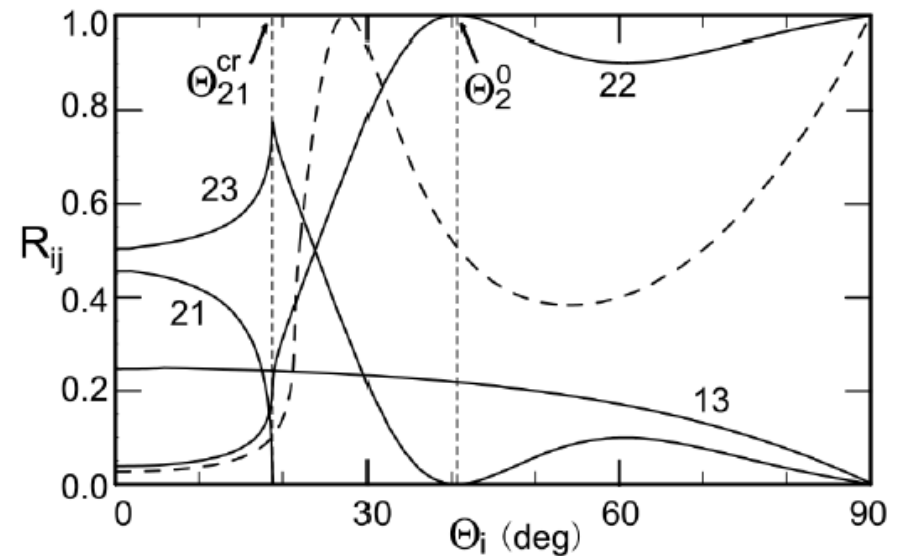
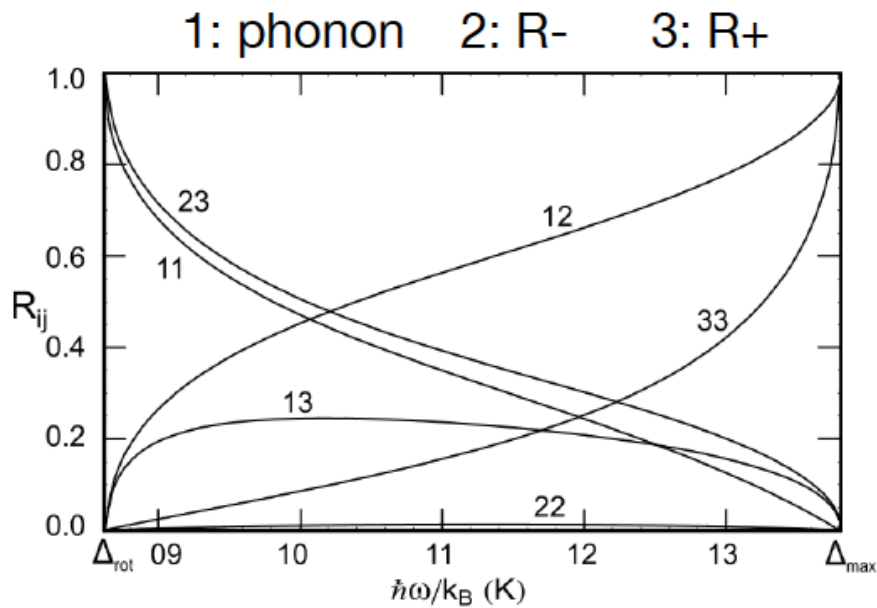
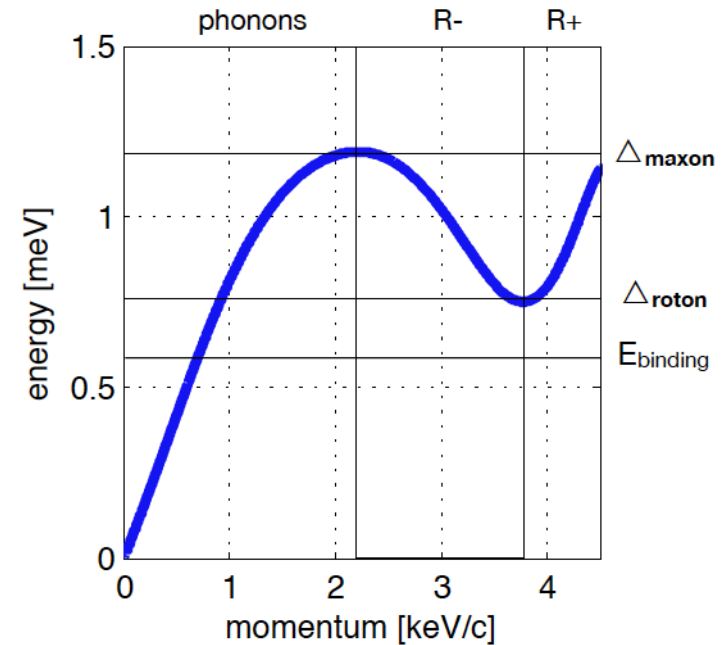
Discrimination using signal ratios

Position reconstruction using signal hit patterns



Phonon/roton
reflectivities have
complex energy and
angular dependence

arXiv:1004.3497v1

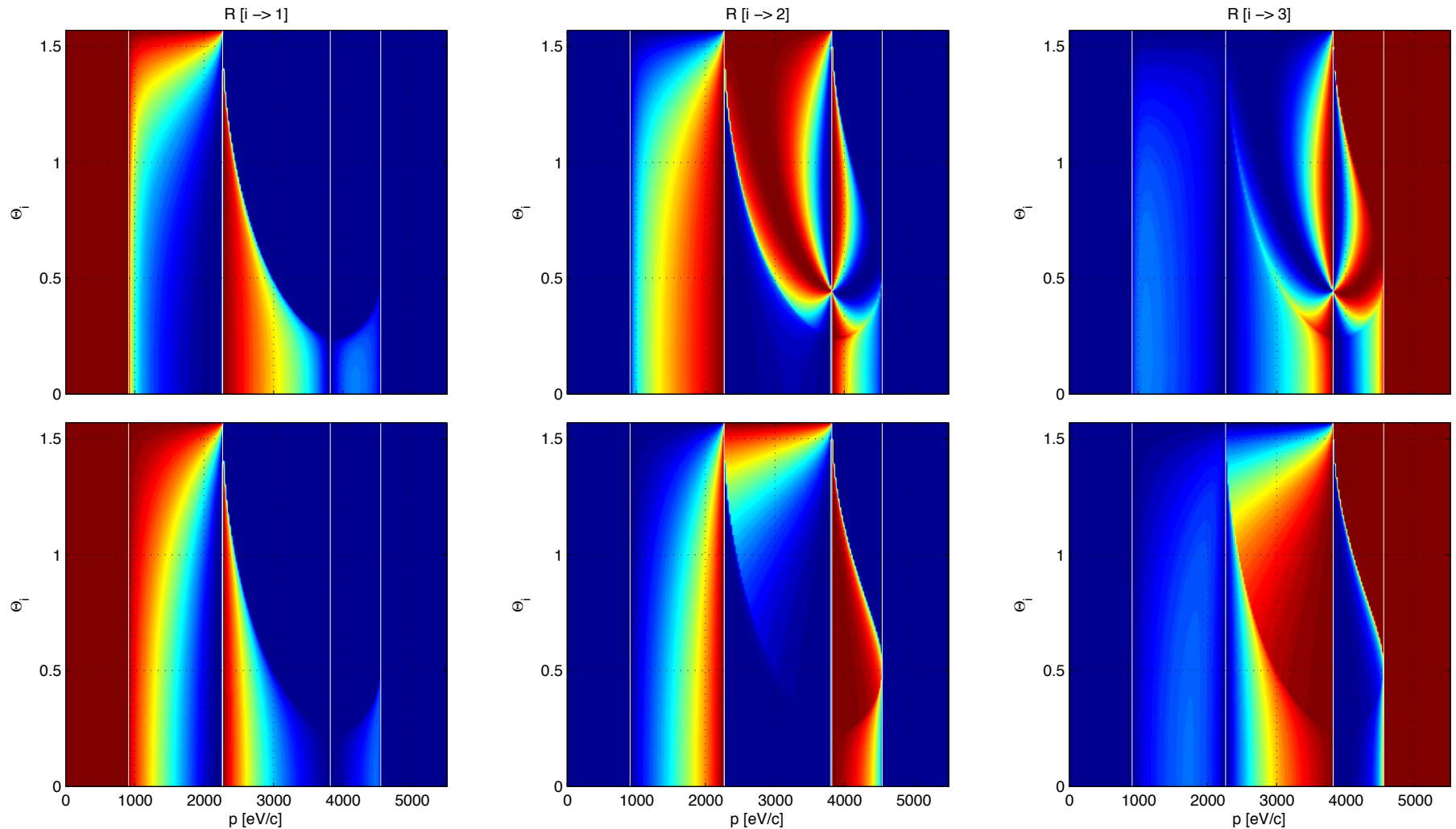


Phonons and rotons can change type when reflecting from surfaces

Calculations based on Tanatarov et al., arXiv:1004.3497

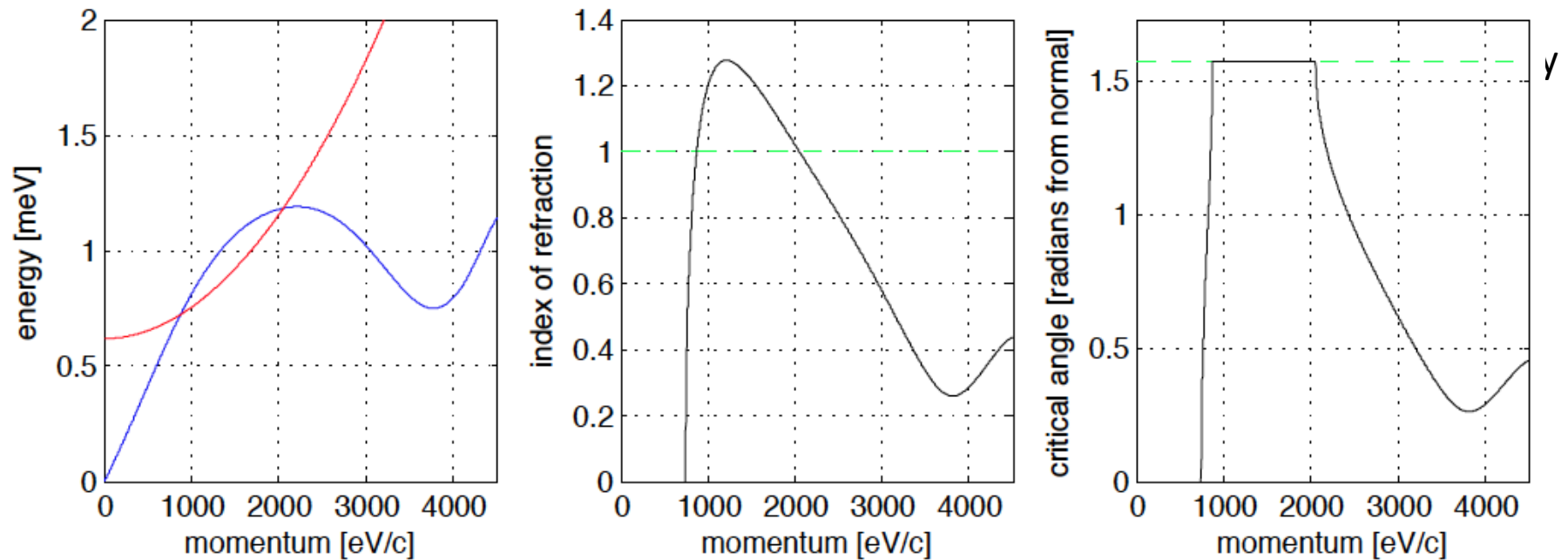
refection mode-change probabilities
(blue=0, red=1)

upper three: solid interface
lower three: vacuum interface

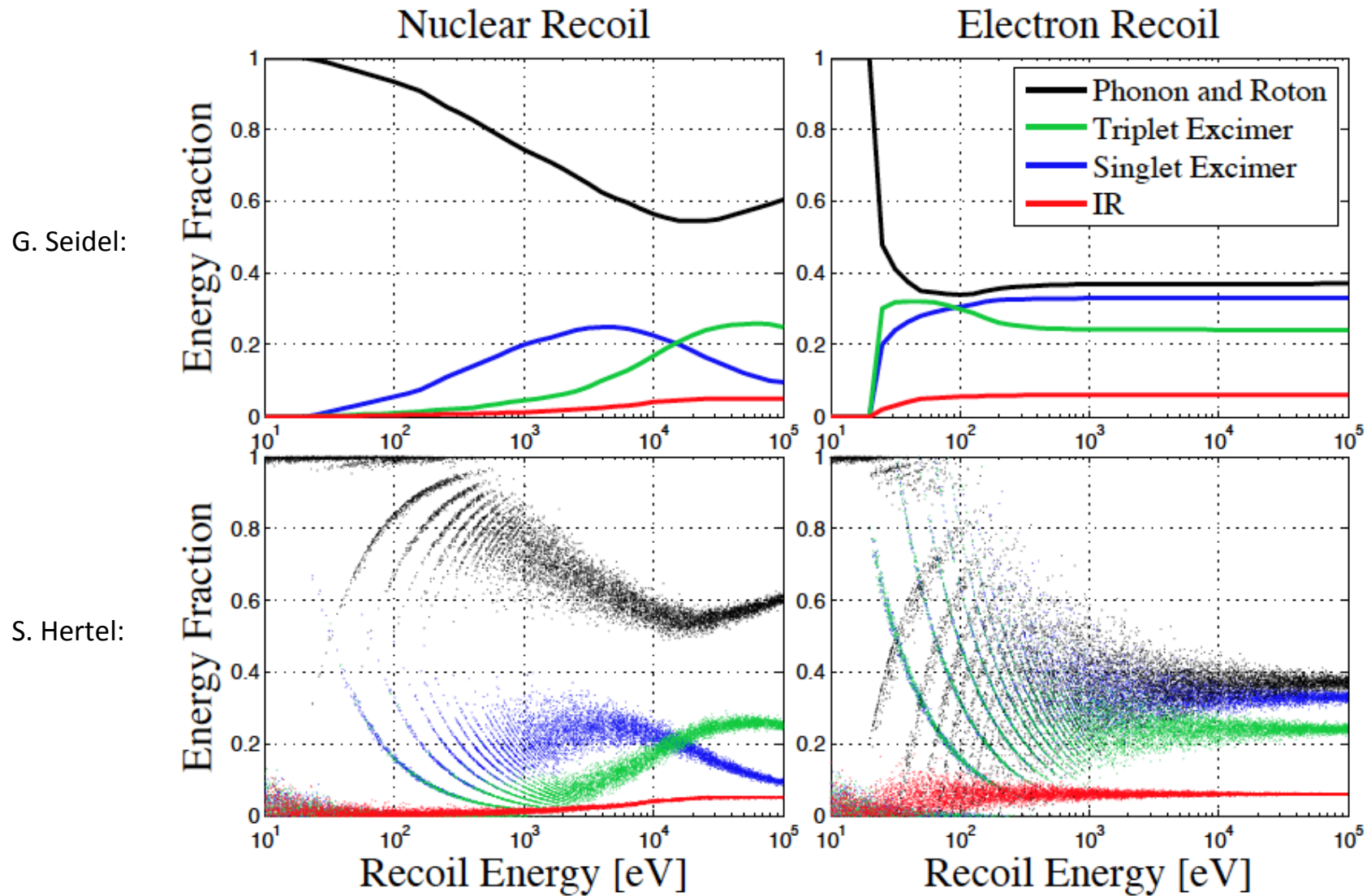


Quantum evaporation from superfluid helium – vacuum interface

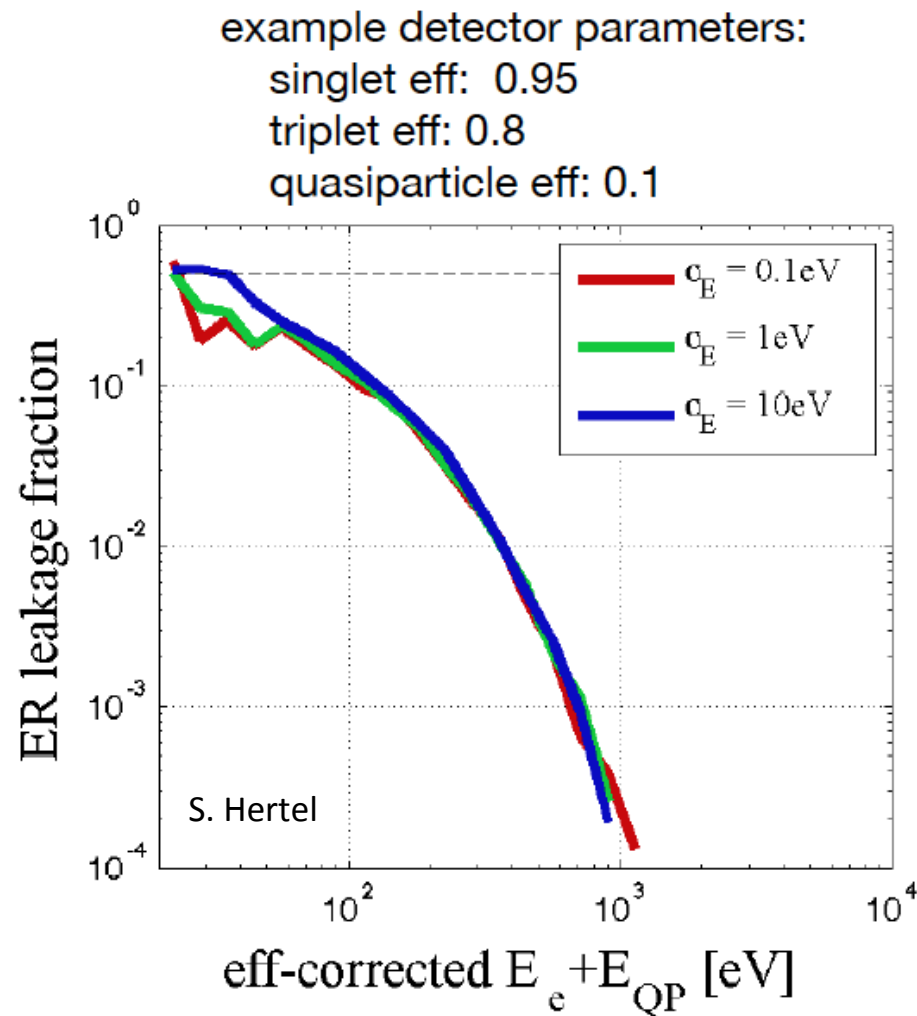
Kinematically-allowed incident angles



Discrimination based on electronic excitation/heat ratio:



Discrimination based on electronic excitation/heat ratio:



Discrimination without electronic excitations?

For very low energies, electronic excitations are heavily suppressed. Need to move to a scheme that doesn't rely on electronic excitations, only heat.

How to get particle identification without electronic excitations?

Possibly could look at roton/phonon ratio, or more generally the momentum distribution of the quasiparticles. Given that ER and NR have different dE/dx , it's quite plausible that they give different quasiparticle distributions. Higher dE/dx should result in a more thermalized (colder) quasiparticle distribution.

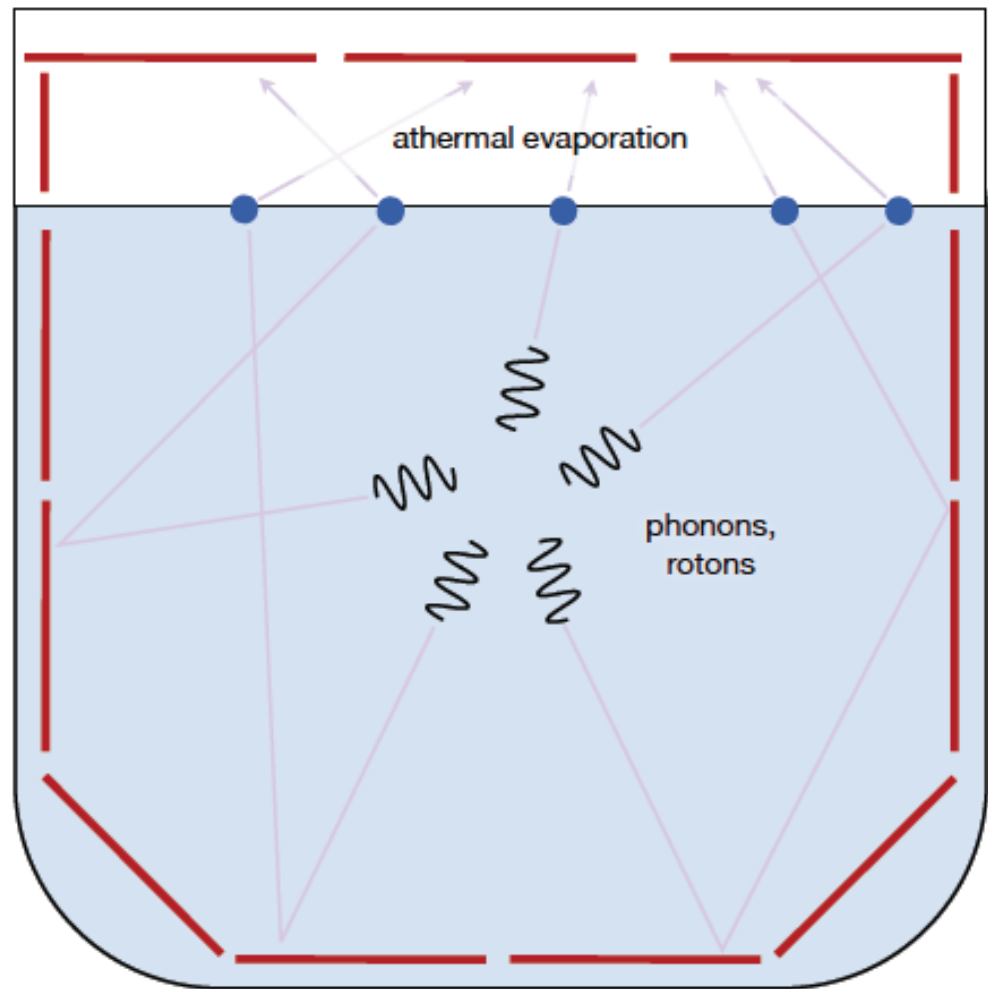
Concept #3

Signal channels:
Phonons
Rotons

Energies down to \sim few meV !!

Discrimination using roton/phonon signal ratios likely. Electron recoils, detector effects, nuclear recoils likely create different roton/phonon distributions.

Position reconstruction using signal hit patterns

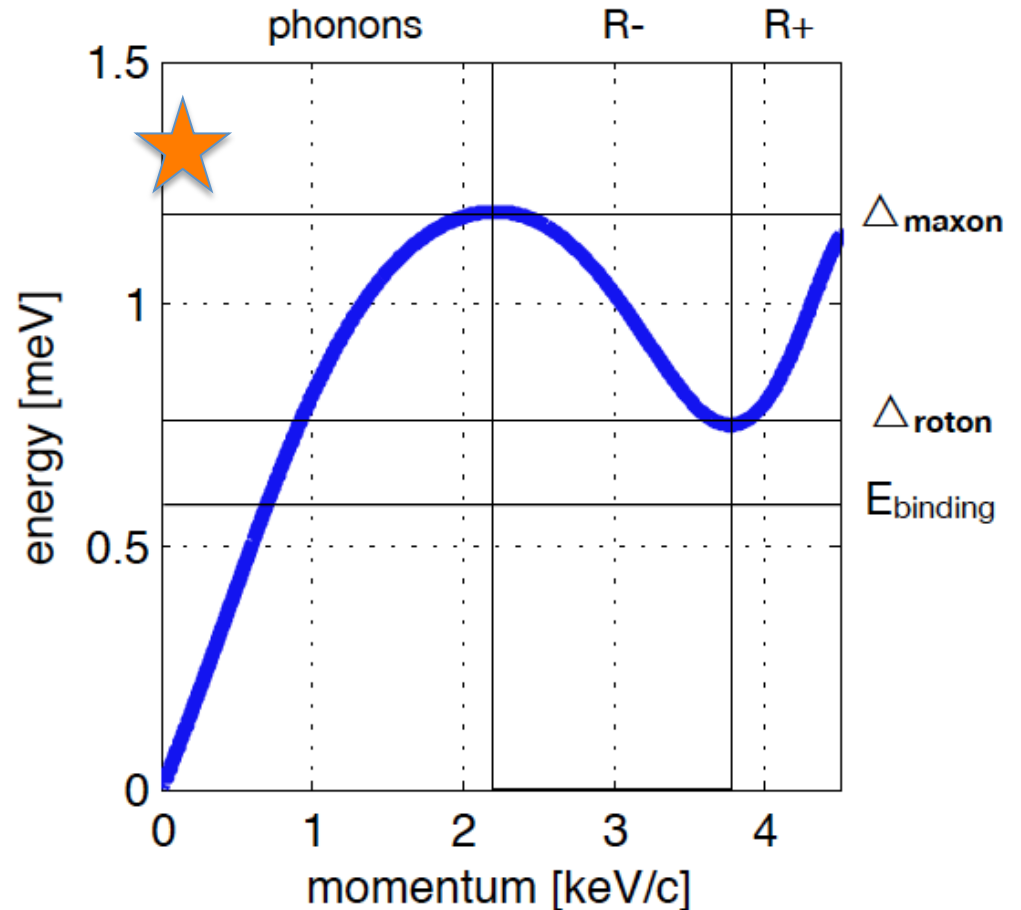


Projected sensitivity to keV-scale dark matter particles

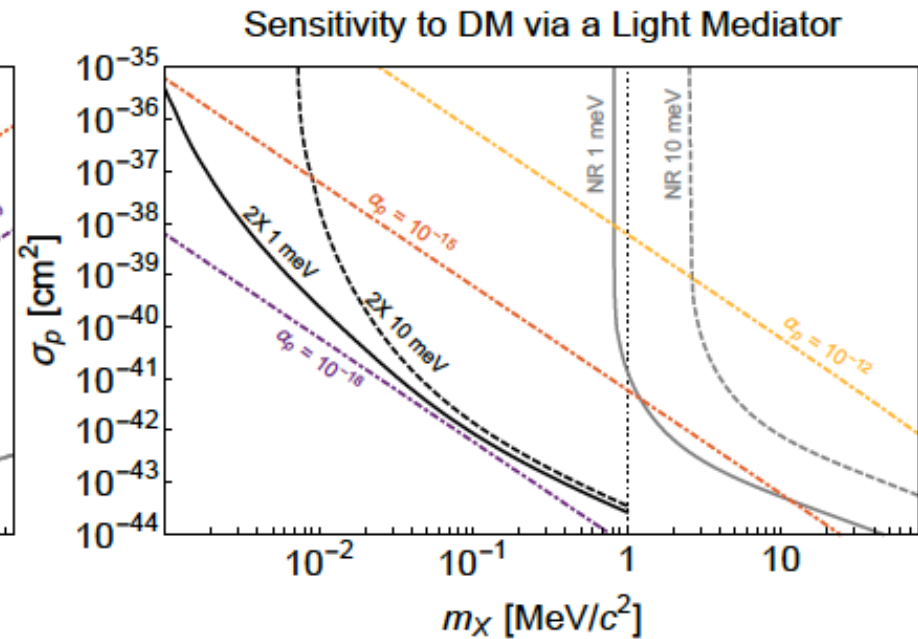
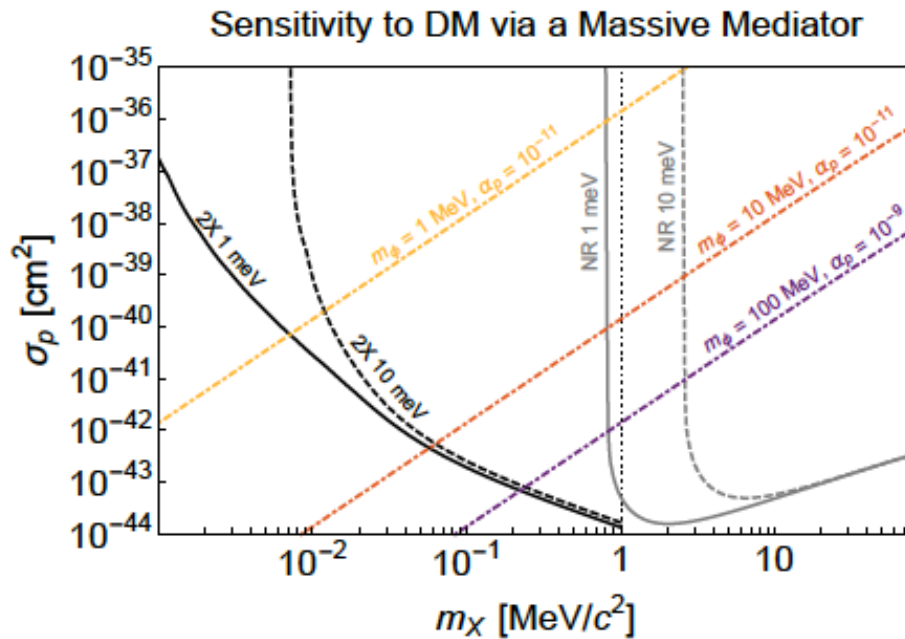
K. Schutz and K. Zurek,
Phys. Rev. Lett. 117, 121302 (2016)
and S. Knapen, T. Lin, and K. Zurek,
arXiv:1611.06228.

Instead of coupling to a single nucleus, couple to virtual mode in the superfluid helium, which in turn decays to multi-excitations

Production of multi-excitations allows high energy transfer from the low-mass, low-momentum dark matter particle



Projected sensitivity to keV-scale dark matter particles



Summary

Superfluid helium has many advantages; this looks like an ideal technology for low-mass dark matter detection.

Multiple signals: scintillation, triplet excimers, charge, rotons, phonons.

Low mass -> good kinematic matching to GeV-scale dark matter.

Multiple advantages for achieving low background:

- intrinsically pure
- Resistant to vibrations
- Can work at zero electric field (no few-electron background)
- ER/NR discrimination power.

Different signals for different WIMP mass ranges:

- Highest energies: Use charge and light?
- Medium energies: Light and heat looks very promising.
- Low energies: Use phonons and rotons, likely still have discrimination.
- Couple to multi-excitations for access to keV mass scale